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LABORATORY MODELLING OF BRAIDED STREAMS

by

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A THESIS

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THE UNIVERSITY OF ALBERTA

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "LABORATORY MODELLING OF BRAIDED STREAMS" submitted by PETER EUAN ASHMORE in partial fulfilment of the requirements for the degree of Master of Science in Geography.

ABSTRACT

Basic hydraulic modelling principles along with a knowledge of channel pattern thresholds allow the development of a model braided stream with flow characteristics and equivalent dimensions of a natural river. Using a constant discharge and flume slope and maintaining approximate equilibrium with an adjustable sediment feed the forms and processes of natural gravel braided rivers are reproduced.

Beginning from a straight trough braiding is initiated by development of a series of alternating bars and scour pools which produce bends of increasing amplitude leading finally to channel division. These mobile, lobate bars which advance downstream by accretion on a lee-side avalanche face, together with the scour pools with which they are necessarily closely associated, are the fundamental elements of the channel pattern. Channel migration and division is a response to bar formation and these adjustments leave portions of the originally mobile bars to be exposed and eroded. Complex units built from these lobate forms show varying degrees of preservation of the original depositional units. Such complexes display a bewildering array of forms arising either from systematic migration and accretion of units as in the case of some medial and point bar complexes, or in a less systematic fashion because of channel avulsion.

Channel division is normally by avulsion or by division on an active bar surface. This is caused by vertical accretion leading to the central portion of the downstream extremity of the lobe becoming inactive and eventually exposed.

The forms identified in the flume channel are similar to

those seen in the Sunwapta River, Alberta (a gravel braided stream) as well as published illustrations of both braided and low sinuosity meandering streams.

Surface sorting of sediment shows several identifiable patterns. Notably bar lobes show a fining downstream on their surfaces and an accumulation of coarse material at the base of the avalanche faces. The pattern may relate to the vertical sorting on the avalanche face which builds downstream. Scour pools show no lag deposits at peak flow but as flow declines a coarse layer is the first to accumulate. Other local sorting patterns include the accumulation of very fine deposits where weak secondary currents are evident and the accumulation of coarse veneers on exposed bar heads. Sediment sorting patterns indicate that mechanisms other than a simple lag principle must be used to explain many elements of size sorting patterns.

Hydraulic geometry measurements of stable channels chosen at random gave exponents of 0.619, 0.261 and 0.120 for width, depth and velocity respectively. These compare well with published data from streams in non-cohesive material. Using d_{50} as the principle scaling factor the model channels and data from the Sunwapta River plotted in the same region of graphs of relative depth and relative width versus dimensionless discharge. This is encouraging in terms of the quality of the modelling and gives added credence to the descriptive information.

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The manual and technical assistance of Mr. Sheldon Lovell and the staff and students of the Graduate Hydraulics Lab. is gratefully asknowledged. Mrs. B. Ford both expertly and conscientiously typed a preliminary and final draft of the thesis. The thesis benefitted from the advise and assistance of the cartographic and photographic staff of the Geography Department. Dr. Bruce Rains suggested some last minute changes in punctuation and style.

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LIST OF SYMBOLS

Symbols used are, as far as possible, those in common use in other publications. Units for some variables (*e.g.* discharge) vary and in those cases the units used are quoted next to the equation where it appears in the text. Otherwise S.I. units are used unless listed specifically.

Symbol		Units
A	channel cross-section area	cm^2
B*	dimensionless channel width $(\frac{W}{d_{50}})$	
c	constant	
D	depth	cm
Dm	model depth	
Dp	prototype depth	
d	grain size	mm
d_{50}	grain size which 50% (by weight) of sample is finer than	
d_{90}	grain size which 90% (by weight) of sample is finer than	
ff	Darcy-Weisbach friction factor	
Fr	Froude number	
g	acceleration due to gravity	
h	head	
H*	dimensionless depth $(\frac{D}{d_{50}})$	
k	constant	
l	bend wavelength	
L	characteristic length	
Lm	model length	

Symbol		Units
Lp	prototype length	
Lr	length ratio $(\frac{Lp}{Lm})$	
P	sinuosity	
p	pressure	
Q	total discharge	cm^3/s
Qr	discharge ratio	
Qs	sediment discharge	
Qw	water discharge	
Q*	dimensionless discharge $\left(\frac{Q}{\sqrt{R_p g\, d_{50}} \cdot d_{50}^{\;2}} \right)$	
qm	discharge/unit width in model	
qp	discharge/unit width in prototype	
qr	discharge/unit width ratio $(\frac{qp}{qm})$	
R	hydraulic radius	
Rp	$\frac{\rho S}{\rho} - 1 \simeq 1.65$	
Re	Reynolds number	
Re*	Grain Reynolds number	
S	slope	
t*	Shields stress	
Tr	time ratio	
v	instantaneous velocity	cm/s
$\bar{v}$	mean velocity $(\frac{Q}{A})$	cm/s
$\bar{v}_m$	mean velocity in model	cm/s
$\bar{v}_p$	mean velocity in prototype	cm/s
W	channel width	cm

Symbol		Units
K	von Karman's constant	
μ	kinematic viscosity	
ν	dynamic viscosity (μ/p)	
ρ	fluid density	
ρ_s	sediment density	
ϕ	phi = $\frac{-\log (mm)}{\log 2}$ (mm) = sediment size	
a, b, c	grain axes	
a, c, k	coefficients in hydraulic geometry equations	
b, f, m	exponents in hydraulic geometry equations	

CHAPTER 1. INTRODUCTION

In contemporary fluvial geomorphology, channel pattern is recognized as an important means by which a river channel can adjust so as to approach equilibrium with respect to several independent variables, particularly discharge, sediment load and size, and valley slope, over comparatively short periods of time (tens of years in some cases). Studies of channel pattern have included several attempts to classify what is essentially a continuum of patterns. Leopold and Wolman (1957) recognized three fundamental plan-forms: braided, meandering and straight. Schumm (1963) devised a classification highlighting the relationships between morphology and sediment type based on the proportions of suspended and bed load carried by a river, while Popov (1964) and more recently Kellerhals *et al.*, (1976) attempted a more refined classification linking morphology and process. There is little dispute, however, that a braided river, while displaying a range of forms, is essentially "one that is divided into several channels which successively meet and redivide." (Leopold *et al.*, 1964, p 281).

Despite the fact that braided rivers have been recognized for many years, they have not received the attention which meandering channels have and thus our understanding of braided river processes falls behind that of meandering rivers. Some studies of bar formation, channel migration and hydraulics exist (Fahnestock, 1963; Hjulström, 1952; Krigström, 1962; Church, 1972; Hein, 1974) but these have tended to raise more questions than they have solved. Geological research has centred on devising facies models for a variety of braided stream

deposits (Miall, 1977).

The lack of information on braided river processes may be partially the result of the difficulties encountered in field studies of braiding, particularly on proglacial streams. Fahnestock (1963), Smith, N.D. (1974) and Hein (1974) describe some of these problems (and hazards) which arise from the fact that at high flow changes in morphology take place extremely quickly and often at rates which make useful measurements impossible to obtain. On the other hand, while individual bars are difficult to trace, the construction of larger complex depositional units takes place over several months or years making it difficult to build up a complete picture of events.

Hydraulic modelling has occasionally been employed by geomorphologists and the problems of braided rivers seem to present an ideal opportunity for study in a controlled laboratory system to provide ideas which can then be applied to natural rivers. Channel pattern problems have been approached by means of model studies previously (e.g. Schumm and Kahn, 1972) but have concentrated on pattern thresholds rather than processes occurring in a given pattern. Because of the necessary reduction in sediment size, the modelling of sandy rivers presents problems with the cohesiveness of the fine-grained sediment required. The modelling of gravel is much simpler, however, as it can be achieved with medium-coarse sand. It is the modelling of gravel braided streams with which this study is concerned.

The objectives of the study were, first, to determine whether a model with the same hydraulic and morphologic characteristics as a natural gravel braided stream could be produced. Second, to describe the processes operating in the river - bar formation and destruction, channel

migration, complex flat construction, sediment sorting, and link these into a comprehensive account of braided river activity at a variety of scales. And thirdly, to obtain information on the hydraulic and morphologic characteristics of the individual anabranches in order to establish whether hydraulic similitude obtained and determine whether laboratory channels respond in the same way to changing independent variables as the natural channels.

CHAPTER 2. CHARACTERISTICS AND CAUSES OF BRAIDING

2.1 Introduction

Research has indicated that although considerable variation exists braided rivers do share certain common sedimentological and hydraulic characteristics. By reviewing these characteristics it should be possible to build up a picture of the nature of braided rivers in general and of braiding in gravel in particular with which the features of the model may be compared. At the same time, examination of meandering/braiding thresholds and the causes of braiding may yield some important information with implications for establishing a braided pattern in the model.

2.2 General Characteristics and Distribution of Braided Rivers

Research to date has suggested some general circumstances under which braiding can be expected to occur and in turn has suggested why braiding should be associated with certain types of environment. Leopold and Wolman (1957), Fahnestock (1963) and Schumm and Khan (1972), in particular, have demonstrated that braiding occurs on steep slopes in non-cohesive material with a high proportion of sediment carried as bedload. Generally speaking, for a given bankfull discharge, braided rivers are expected to occur on steeper slopes than meandering and straight channels (Leopold and Wolman, 1957; Lane, 1957; Henderson, 1961, 1966). Braided rivers are characterized by low sinuosity channels with high width/depth ratios (as high as 800 in some cases). The nature of the hydrograph, which in many braided rivers fluctuates rapidly over a large range, is often mentioned as an important feature of braided

rivers (for example, Doeglas, 1962; Fahnestock, 1963; Smith, N.D., 1974). These attributes suggest certain types of environment in which braided rivers should be common. Church and Gilbert (1975) indicated that a basic cause of braiding could be thought of as a local inability to transport the imposed sediment load and such a situation may be found in many sand or gravel rivers transporting sediment along their beds, or in areas associated with declining competence such as alluvial fans or deltas and ephemeral streams experiencing flash floods. Thus we might expect braiding in many areas of the world and the published examples show a range from small gravel proglacial streams on steep slopes to huge rivers such as the Brahmaputra transporting sand and silt.

2.3 Hydrology

Braided rivers show a wide range of types of hydrologic regime dependent on their geographic location but one characteristic which is commonly commented on is the tendency for braided rivers to show more variability in discharge than other stream types. Thus Miall (1977) in referring to an analysis by Wright *et al.*, (1974) asserts that of the rivers investigated those dominated by braiding have a higher flood peakedness, higher total discharge range and higher monthly discharge variability than the others. It is certainly true that some braided rivers, especially proglacial and ephemeral examples, show wide and rapid (diurnal) fluctuations in discharge (Arnborg, 1955; Church, 1972; Smith, N.D., 1974), but it is still not clear what relevance these hydrologic characteristics have to braiding itself or to the details of the processes occurring in braided rivers. Indeed, it has still not been established whether we can generalize and say that high discharge

variability is a necessary characteristic of braided rivers.

2.4 Morphology

2.4.1 Pattern variability. As part of a continuum of channel patterns rivers which fall into the category of braiding range considerably in appearance from the large sandar plains described by Hjulström (1952) to those verging on a single sinuous channel. In addition, braiding in gravel may tend to be rather different in form from that in sand. Within a particular river, however, the pattern can also change through the influence of slope, sediment size and bank resistance. Cases of changes from meandering to braiding over short distances are common (Mackin, 1956; Leopold and Wolman, 1957), and in the same way the braiding pattern may change. Thus Williams and Rust (1969) have described how the Donjek River, in the Yukon, shows three different patterns ("zig-zag", straight braided, and meandering with internal braids) over a short distance but were unable to reach any conclusions about the reasons for the changes. The Amite River (McGowan and Garner, 1970) and several low sinuosity rivers in Scotland (Bluck, 1976) show braiding tendencies which are inhibited by banks resistant to erosion but seem to have bedforms similar to those found in some braided rivers. Fahnestock (1963) has also shown that a given reach of a river may show changes in pattern with time (in this case from meandering to braiding and back again) related to the discharge and sediment load in any given period. Thus, there are all shades of braiding but they share certain common features.

2.4.2 Channel network topology and topography. The complex of channels in braided rivers does have some order in terms of the form of the

network and in a hierarchy of channels and topographic levels apparently related to discharge stage. Commonly one main channel occurs carrying a larger proportion of the discharge than any other although occasionally the pattern is dominated by two or more major channels of approximately equal size (Fahnestock, 1963; Krumbein and Orme, 1972; Rust, 1972; Boothroyd and Ashley, 1975). At low flows these may be the only channels active.

Krumbein and Orme (1972) and Howard *et al.*, (1970) have shown, by producing computer simulations of braided rivers with the same topological characteristics as natural rivers, that the network is controlled by apparently random processes which nevertheless produce some regularity in the network. One of the more notable features is the presence of regularly spaced contractions or nodes in the network where several channels rejoin and then divide again. It is possible that the nodes are spaced in some way related to the wavelength of the bends in the channels although no analysis of this kind has been carried out. Coleman (1969) and Chien (1961) have reported these features in the Brahmaputra and Yellow Rivers and have demonstrated that they act as important control points in channel migration.

Williams and Rust (1969) and Boothroyd and Asley (1975) have suggested that a heirarchy of channels of different sizes may be identified and that in addition a series of topographic levels related to different frequencies of inundation are also common. Some levels are so infrequently inundated that they could be regarded as terraces. Such terraces have been described in several proglacial rivers (Fahnestock, 1963; Williams and Rust, 1969; Church, 1972; Knighton, 1976) and they lend support to Leopold and Wolman's (1957) conclusion

that braiding is not restricted to an aggradational environment and may be an equilibrium condition. In fact, this leads to a difficulty in extrapolating present day processes observed in equilibrium or degradational environments to the interpretation of ancient aggradational deposits, particularly in terms of the preservability of various features.

2.4.3 Channel and pattern migration. Although channel migration is necessarily related to channel processes and bar formation, some aspects can be treated separately. Two basic mechanisms of migration exist, lateral erosion and avulsion. Lateral erosion is very evident in braided streams (Hjulström, 1952; Krigström, 1962; Fahnestock, 1963; Williams and Rust, 1969; Church, 1972) but figures for typical rates of erosion are rarely quoted. Measurements are available from the Brahmaputra and Yellow Rivers (Chien, 1961; Coleman, 1969) both of which show rates of several thousand feet per year with bank erosion being most effective on the falling stage. Chien (1961) has noted the influence of the spacing of nodes on channel migration and braiding. The wider the spacing of the nodes, the greater the freedom to migrate laterally and the greater are the opportunities for further flow division (Fahnestock, 1963; Krumbein and Orme, 1972). The second migration process, avulsion, occurs by aggradation within a channel causing spilling of water over into an adjacent abandoned channel or cutting of a new channel. Lateral erosion can also play a role here. Avulsion, therefore, produces much more rapid and larger shifts in channel position and is less predictable than lateral migration. Chien (1961) has suggested that during high discharges avulsion may be more common while at lower discharges migration is primarily via lateral

erosion. Avulsion has also been described in proglacial braided streams (Church and Gilbert, 1975). Not only may individual channels shift but often the whole channel system may show migration in one direction. This general pattern shift is very common in braided rivers on alluvial fans (Gole and Chitale, 1966; Boothroyd and Ashley, 1975).

2.4.4 Bars. As the primary sedimentary features in braided rivers the various types of bar have been subject to considerable study by both geomorphologists and geologists and the result has been a certain amount of confusion because of a plethora of bar types and bar classifications. This is partially a problem of differing classifications and names being aimed at solving rather different problems, particularly involving the geomorphological tendency to see the external form of the bar in three dimensions and the geological problem of recognizing bar types which can be identified in two dimensional exposures showing primarily the internal structure. Despite attempts to produce some order among the chaos (see for example, Miall, 1977) there is no evidence of the adoption of a universal terminology for bars in braided rivers. Confusion also arises when deciding what constitutes a bar in the first place. Generally speaking, however, a bar can be regarded as a bedform which may or may not be exposed at a particular stage and which has dimensions of the same order as the channel(s) in which (or between which) it occurs (Allen, 1968). In Jackson's (1975) terminology they are mesoscale features. What is interesting is that in recent years it has become increasingly common to regard bars (and indeed, channel pattern as a whole) as dynamic features related to higher discharge events and in the same framework of instability as other smaller scale bedforms. The importance of the hydrodynamics of bars as the cause of

channel instability, migration and channel division is beginning to be recognized (see for example, Rust, 1972; Hein, 1974; Boothroyd and Ashley, 1975). The result is that we are left with two rather different views of channel bars - one considering them as static depositional features splitting up channels and shaped by stream erosion; the other seeing them as dynamic bedforms. Perhaps these two different perspectives have caused or at least contributed to some of the confusion evident in studies to date.

2.4.4.1 *The unit bar concept.* The idea of unit bars was proposed by Smith, N.D. (1974) in an attempt to distinguish fundamental depositional features which might be preserved in the geological record. They are regarded as the smallest recognizable bars of a primarily depositional character, *i.e.* they show only minor modification by erosion. These units can then be viewed as the building blocks for more complex bars with multi-stage erosional and depositional histories. Unfortunately the four types of unit bar: longitudinal, transverse, diagonal and point bars do not apparently have clear differences which enable them to be distinguished in ancient deposits. Problems also arise because other workers recognized longitudinal bars but in several instances suggested that erosional remnants of other bars which are elongated parallel to the flow should also be called longitudinal bars (see for example, Boothroyd and Ashley, 1975). While agreeing with Smith's general idea, Hein (1974) and Hein and Walker (1977) suggested from a geological point of view that it may be more useful to distinguish, for example, bars with avalanche faces and those without. Nevertheless, the idea of unit bars remains a useful one for the purposes of organizing our thinking about the structure of braided stream deposits.

Apparently with the unit-bar concept in mind, Miall (1977, p. 12) proposed an "all encompassing, but simple classification" which, although it may not entirely live up to this description, still provides a useful basis for summarizing the existing literature on braided river bars and is used here.

2.4.4.2 *Longitudinal and diagonal bars.* The term longitudinal bar has been used on many occasions (Leopold and Wolman, 1957; Williams and Rust, 1969; Rust, 1972; Church, 1972; Smith, N.D., 1974; Hein, 1974; Gustavson, 1974; Boothroyd and Ashley, 1975) and is usually applied to bars which are approximately diamond-shaped in plan and elongated parallel to the flow. They commonly owe this shape more to erosion than to deposition (despite Smith's (1974) classification). The term apparently owes its origin to Leopold and Wolman (1957) who first described the mechanism of formation which begins with a local decrease in competence in the centre of the channel (for whatever reason) producing deposition of the coarsest fraction of the bed load. This then serves as a trap for other particles and the bar builds downstream and vertically while the channels on either side tend to incise and lower the water surface, thereby exposing the bar. Since this original description, the process has been recognized in several studies (Ore, 1963; Schumm and Khan, 1972 - both flume experiments; Williams and Rust, 1972; Smith, N.D., 1974). The longitudinal bar tends to be most common in gravel braided streams, indeed all descriptions seem to be limited to gravel streams. Their internal structure consists of massive, crudely horizontally bedded gravels indicating construction from sheets of gravel in transport (Rust, 1972; Hein, 1974). They rarely show foreset margins. Grain size tends to decrease downstream and upwards although this simple trend is often

complicated by later events. The deposits tend to be grain-supported open-work gravel. Smith, N.D. (1974), Church (1972) and Hein (1974) also describe a diagonal bar formed in a similar way to longitudinal bars but characterized by flow oblique to the general stream flow direction. They are common in bends and at channel junctions but apparently have no other features which may distinguish them from longitudinal bars. Krigström (1962) recognized similar features in channel bends but gave them no specific name.

2.4.4.3 *Linguoid and transverse bars.* This second category of bars is most commonly associated with, but by no means limited to, sandy rivers. Nor are they limited to braided rivers: McGowan and Garner (1970) and Gustavson (1978) recognized similar forms in gravel-bed meandering rivers, while Karcz (1972) and Hicken (1969, 1972) have suggested that point bars (point 'dunes') may be built in sandy, single channel rivers by this kind of bedform.

For gravel rivers, Rust (1972), Klimek (1972), Smith, N.D. (1974) and Hein (1974), have all described transverse type bars occurring in well-defined channels, while Fahnestock and Bradley (1973) recorded the passage of such forms in the Knik River, Alaska. The important feature of both linguoid and transverse bars is their gently dipping stoss face and steep lee avalanche face. Transverse bars tend to have straighter crests than linguoid bars but those described in gravel rivers show a lobate or fan-like appearance downstream of scour chutes. Fahnestock (1963) observed similar features in the White River and referred to them as "noses" while Culbertson and Scott (1970) monitored the movement of transverse bars down a conveyance channel with a sand bed and suggested that coalescence of dunes may be responsible for their formation.

Linguoid bars tend to be limited to sand bed rivers (Brice, 1961; Collinson, 1970; Smith, N.D. 1971, 1972; Boothroyd and Ashley, 1975). The linguoid bars illustrated by Church and Gilbert (1975) should probably be regarded as longitudinal or compound bars in this scheme. Cant (1975) Walker (1976), and Cant and Walker (1978) have described related forms in the South Saskatchewan River with foreset slopes oblique to the flow direction. Galay and Neill (1967) have observed similar bars in the gravel rivers of Alberta, especially the North Saskatchewan. In terms of internal structure there is probably little to distinguish transverse and linguoid bars, the predominant structure being planartabular cross-bedding. Sediment sorting on these bars has rarely been described but Culbertson and Scott (1970) suggested that sandy transverse bars fine downstream while Smith (1974) and Hein (1974) suggested the same for gravel transverse bars.

2.4.4.4. *Compound bars*. These are larger scale features than the unit bar types discussed above. They consist of a complex of unit bars and rarely has any sort of systematic discussion of their formation been attempted (but see Kirgström, 1962; Bluck, 1974, 1976; Cant and Walker, 1978). A variety of names have been applied to these features - point bars, side bars, lateral bars, medial bars and braid bars (Allen, 1968). They are constructed from lateral and vertical accretion of bar units and also owe their external morphology to erosion.

2.4.4.5 *Hydrodynamics of bars*. While several workers have alluded to the fact that some bars may be regarded as dynamic bedforms built during high discharge stages and dissected at lower stages, analyses of the type common for smaller bedforms have not been attempted. This is because of the great complexity and variability of these forms and also

because of the problems of instrumenting a rapidly changing three-dimensional landform. Smith, N.D. (1971) was able to suggest a maximum bar size for a given discharge on transverse sand bars on the Platte River but an attempt to complete a similar analysis on the gravel of Kicking Horse River (Smith, N.D., 1974) was frustrated. Hein (1974) apparently had more success in instrumenting transverse bars in the Kicking Horse River but limited her study to a simple two-dimensional (along the axis of the bar) analysis which even so produced rather inconclusive data beyond relating bar migration rates to discharge fluctuations and rate of change of velocity. Thus even the most basic quantitative data on these bed-forms is still lacking.

2.4.4.6 *Comments on bar classification.* The above discussion has served to suggest some anomalies in the use of the word 'bar' and in the use of the various terms applied to types of bars. There seems to be some confusion as to whether we should consider bars simply as exposed remnants following channel division or as bedforms produced by scour and deposition and which migrate laterally and downstream. We should probably see them as both of these, the former being later stages of the lobate bedforms. However, to use the same term for both forms (*e.g.* as in the case of longitudinal bars) is bound to cause confusion. Perhaps if it were recognized that these two bar forms, which are actually different stages of the same depositional features, existed we could arrive at a more reasonable classification.

2.5 Sedimentology of Braided Rivers

The braided stream depositional environment is diverse in its characteristics and extremely complex in construction showing a great

transience in the contemporary case which is reflected in rapid vertical and lateral facies changes in ancient deposits. The geological approach has been to recognize specific facies and facies assemblages in modern and ancient deposits and to relate these to each other, often using statistical techniques. A wide range of sedimentological studies of modern braided streams exist, the larger number referring to gravel streams. However, very few studies have involved a direct comparison of a particular ancient deposit with its likely modern counterpart and only occasionally (*e.g.* Eynon and Walker, 1974) has it been possible to give detailed descriptions of individual bars and associated deposits in Pleistocene or ancient deposits.

Research in fluvial sedimentology now allows a distinction between meandering and braided river deposits to be made largely on the basis of:

1) the thickness of the coarse member of each cycle;

2) the proportion of overbank deposits;

and 3) the abundance of foreset bar stratification.

However, it is also apparent that similarities in the sedimentology of low sinuosity meandering streams and braided rivers in similar material may make it difficult to distinguish between them. Despite this fuzzy middle ground between meandering and braiding it is possible to compile a series of facies and facies assemblages typical of braided rivers and to distinguish between gravel and sand rivers and perhaps recognize some intermediate types (Miall, 1977). In terms of external bar morphology and formation it is apparent that a great deal of similarity may exist between sand and gravel rivers.

2.5.1 Braided river facies and sequences and their interpretation. Miall (1977) suggested several facies which commonly occur in braided rivers.

2.5.1.1 *Massive gravel.* This facies has been recognized in virtually every study of gravel braided rivers and is by far the dominant facies in these streams. Its structure, sorting and imbrication may vary but in general it is clast supported (suggesting deposition in the absence of fine material) and crudely horizontally bedded. It is commonly regarded as a longitudinal bar facies but is probably the result of deposition from any kind of transport of gravel in a sheet-like form (Rust, 1972).

2.5.1.2 *Cross-bedded sand and gravel, horizontally laminated sand.* These facies are apparently the product of a variety of bedforms present in braided rivers. The large-scale cross beds are produced by migration of the avalanche faces of transverse/linguoid bars, while smaller scale units belong to dunes and the horizontal sand to plane bed conditions.

2.5.1.3 *Trough cross-bedded gravel and shallow scour fill.* These two are regarded as scour and fill facies. There is no shortage of observations of small and large scale scour of various types in modern rivers (Williams and Rust, 1969; McGowan and Garner, 1970; Smith D.G., 1973; Fahnestock and Bradley, 1973; Gustavson, 1974; Hein, 1974) related to bars and to channel convergence. Some of those observed are several feet deep and could easily account for the scour features described in ancient deposits (*e.g.* Cant and Walker, 1976).

2.5.1.4 *Other facies.* These consist of ripple laminated sand, and clay and silt deposits characteristic of falling stage and standing

water. They are an integral part of any braided stream deposit.

Because we are dealing with a continuum of channel pattern types and a wide range of possible facies assemblages and sequences within and between streams, the characterization of typical braided stream deposits (*i.e.* a comprehensive facies model) is impossible to formulate at present (Cant and Walker, 1976), but nevertheless it is possible to suggest in general terms the types of assemblages expected.

2.5.2 Sand rivers. The sedimentology of sandy braided rivers has been investigated by a number of people (Collinson, 1970; Smith, N.D., 1971, 1972; Williams, 1971; Cant and Walker, 1975, 1978; Walker, 1976; and Boothroyd and Askley, 1977). Generally speaking, the deposits are dominated by dune and planar tabular or planar cross-bedded bar deposits. Miall (1977) referred to this as the "Platte" type (after Smith's N.D. 1971, 1972 study of the Platte River). Miall (1977) also identified the "Bijou Creek" type representing sandy ephemeral streams subject to flash floods and dominated by thick planar bedded sand units (*e.g.* McKee *et al.*, 1967; Williams, 1971).

2.5.3. Gravel rivers. Numerous sedimentological studies of gravel rivers exist (Krigstrom, 1962; Ore, 1963; Williams and Rust, 1969; Banerjee, 1970; Klimek, 1971; Costellor and Walker, 1972; Smith, N.D., 1974; Gustavson, 1974; McDonald and Bluck, 1974; Hein, 1974; Boothroyd and Ashley, 1975; Hein and Walker, 1977) and most agree on certain common features. In particular, individual bars tend to show fining-upwards and downstream (although explanations for both are generally lacking). Massive horizontal gravels with occasional crossbeds (Hein and Walker, 1977) dominate the deposits with occasional planar and trough crossbedded sand wedges in the lee of bars and on other reactivations surfaces

and channels (Eynon and Walker, 1974). Lag gravels in scour holes may also occur (Hein and Walker, 1977). Miall (1977) referred to this as the "Scott" type - a proximal braided stream. The deposits described by Williams and Rust (1969) seem to lie halfway between the "Platte" and "Scott" types in showing a larger quantity of sand facies and consisting of a series of units showing fining upwards from massive gravels to stratified sands and finally silts. While fining upwards is common, the complexity of braided streams means that sequences are often truncated and partially removed making cross-cutting surfaces and a rapid change of grain orientations common. Costello and Walker (1972), Rust (1972), and Bluck (1976) have identified coarsening upward sequences in braided rivers although their origin is disputed. Costello and Walker (1972) proposed that avulsion (*i.e.* an increasing energy environment) could produce a coarsening upward sequence while Bluck (1976) identified coarsening upwards with migration of bar-head gravels over finer-bar-tail deposits.

It is possible for the change from gravel to sand environment to occur along one river (especially on alluvial fans). This change in grain size is usually accompanied by a change in bar types (towards the linguoid form) and often a reduction in bed topography (Smith, N.D., 1971; Boothroyd and Ashley, 1975). For this reason Miall (1977) refers to the types as being proximal and distal respectively although there is not necessarily any connotation of distance from the source attached to these terms. While it is possible to identify general stream types, it seems dangerous at present to attempt a classification of the kind attempted by Miall (1977) because of the possibilities it presents for proliferation of type-deposits which may only add to the present

confusion. The classification may be useful as a start in organizing the available information but as general facies models from which predictions can be made they are worthless. There may also be a dangerous tendency to try and fit other deposits into the existing classes.

4.5.4 Directional variability. Low sinuosity streams inevitably show lower directional variability than fully meandering streams but there is also a tendency for directions and variability to be more erratic. Different components of the system show different variances because of the changes in flow direction which take place as discharge changes (Collinson, 1970; Rust, 1975; Bluck, 1974, 1976). Thus, for example, channels show a low variability compared with ripples. This is useful to some extent because it may be possible to distinguish similar stratification types of different origins *i.e.* from different bedforms on the basis of directional variability (Walker, 1976).

2.6 Characteristics of Braided River Channels

Channel form is the result of the interaction between channel boundaries and water and sediment discharge. The factors involved are numerous. In the time period needed for the establishment of regime (Blench, 1969) or grade (Mackin, 1949), the main independent variables are the fluid temperature, and sediment particle density, the water discharge, bed material transport and washload and the channel slope (which may be dependent or independent) (Church and Gilbert, 1975, p. 69). Leopold and Wolman (1957) expressed the same idea in terms of the interaction between nine variables; discharge (amount and variability), sediment load (amount and grain size), width, depth, velocity, slope

and bed roughness. In the long term, climate, vegetation and geology must also be considered (Schumm, 1968). Unfortunately, at present there are not sufficient relationships available to provide a unique solution in every case (Maddock, 1969, 1970) with the result that channel form has been investigated not only from an empirical viewpoint but also from a probabalistic viewpoint (Langbein, 1964) and from the point of view of minimization of energy expenditure (Yang, 1971) and variance minimization (Langbein and Leopold, 1961). In braided rivers the instability of individual anabranches makes application of regime theory or analysis of channel form very difficult but it is probably that the majority of channels do reach an approximate equilibrium for at least a short time.

2.6.1 Channel shape. Channel shape is an important feature of braided anabranches and is essential to an understanding of braiding. The high width/depth ratios are commented on in all studies of braiding (*e.g.* Leopold and Wolman, 1957; Fahnestock, 1963; Klimek, 1971, Church, 1972). High width/depth ratios are characteristic of channels in non-cohesive sediment with a high proportion of sediment carried as bedload and in which adjustment to the imposed load of water and sediment takes place primarily by increasing width (Schumm, 1960; Wolman and Brush, 1961). Width will increase until shear at the bank decreases below some threshold (bed shear increases accordingly). The tendency for excessive channel widening appears to be the immediate cause of channel division. Channel form itself varies but in straight reaches tends to be trapezoidal with concave banks and a flat bed (Wolman and Brush, 1961; Fahnestock, 1963). However, in areas undergoing aggradation or degradation, and in bends, the channel may take on a

variety of shapes (Fahnestock, 1963; Hein, 1974). Commonly, in wider channels, the bed is convex taking the form of an incipient bar.

2.6.2 Hydraulic geometry. A number of studies of the hydraulic geometry of braided river anabranches exist but only Church and Gilbert (1975) have published data for sand-bed rivers. Of the studies available (Leopold and Wolman, 1957; Fahnestock, 1963; Church, 1972; Nordseth, 1972; Knighton, 1976) the most important feature seems to be the unusually high rate of increase in velocity with discharge at a station. Church and Gilbert (1975) and Knighton (1976) have indicated that a high rate of change of velocity is associated with a large and rapidly increasing sediment load and is, therefore, an adjustment in keeping with the necessity to maintain a high bedload transport rate. The rapid increase in velocity with discharge at-a-station is probably tied in with the abnormally high rate of decrease of resistance caused by a reduction in form resistance and the lower boundary resistance offered by a mobile channel bed (Church and Gilbert, 1975). Because of the nature of the braided channel system, it is not possible to formulate a proper downstream hydraulic geometry but a random sample of channels at bankfull discharge is closely equivalent to a downstream hydraulic geometry and the studies available (*e.g.* Fahnestock, 1963) suggest that the velocity exponent downstream is lower than the exponent at-a-station and that the width exponent increases accordingly.

The changes in channel geometry at channel divisions is also of interest but much of the available data (Rubey, 1957; Leopold and Wolman, 1957; Brice, 1961; Axellson, 1967; Nordseth, 1971, Church, 1972) is contradictory. This may be partially the result of different

definitions of parameters. Rubey (1957) and Brice (1961) found that width decreased and depth and velocity increased at channel divisions. Leopold and Wolman (1957) and Nordseth (1971) found an increase in width and a decrease in depth downstream from channel divisions. Church (1972) found little difference in channel shape above and below channel divisions, suggesting that anabranches adjust rapidly after flow division. Church (1972) did, however, find a difference in hydraulic geometry between braided and non-braided reaches, and Nordseth (1971) also noted a change in the exponents of hydraulic geometry below channel division (notably an increase in the velocity exponent).

2.6.3 Riffles and Pools. Braided rivers often show a riffle-pool structure similar to that of meandering streams with riffles being associated with bars and pools formed as chutes or scour holes alongside or downstream from bars (Church and Gilbert, 1975). It is not clear, however, whether they function in the same way as their counterparts in meandering rivers, partially because their position and existence are so unstable. They are, however, important elements in sediment transport (Church and Gilbert, 1975).

In addition, scour holes at channel junctions are common (Fahnestock and Bradley, 1973; Hein, 1974; Smith D. G., 1973; McDonald and Banerjee, 1975) and often have bars deposited downstream from them. Gustavson (1974) commented on finding mysterious small scour holes, often on bar surfaces, with no apparent explanation for their formation apart from scour around obstructions such as ice blocks.

2.6.4 Long profile. The only detailed analysis of the long profiles of braided rivers, apart from the common observation of changes in local slope over bars and through channel divisions, is that by Church

(1972). He suggested that the Baffin Island sandar show a stepped profile on a larger scale than the bar-pool sequence. The flatter areas are zones of extensive deposition and flow divergence while the steep areas are zones of erosion and convergent flow. Church (1972) proposed that this was a hydraulic response to high sediment load which allows deposition without reducing the general slope of the river.

2.6.5 Channel behaviour and the causes of braiding. The summary of braided river behaviour and characteristics begins to give us some insight into why a river should be braided. The literature contains a series of suggestions most of which centre around factors such as steep slope, dominant bedload, non-cohesive bed and banks and large width/depth ratios (Fahnestock, 1963). The interrelations of several of the factors complicate the problem.

2.6.5.1 *Slope*. One of the fundamental factors involved in braiding is related to the fact that for a given discharge braiding tends to occur on steeper slopes than meandering. Lane (1957) and Leopold and Wolman (1957) both derived slope thresholds above which braiding would occur for a given discharge. These were:

$$S = 0.010/\sqrt[4]{Q} \qquad \text{(Lane, 1957)} \qquad (1)$$

$$\text{and } S = 0.06\ Q^{-0.44} \qquad \text{(Leopold and Wolman, 1957)} \qquad (2)$$

Henderson (1961, 1966) confirmed these findings and proposed a refinement introducing sediment size as a further (and necessary) component:

$$S = 0.44\ D^{1.15}\ Q^{-.46} \qquad (3)$$

This was derived from empirical data while a second equation derived from consideration of tractive force criteria for stable channels gave:

$$S = 0.64\ D^{1.14}\ Q^{-0.44} \qquad (4)$$

The agreement between the two is remarkable and, according to Henderson (1966, p. 471), by no means coincidental. In other words, at steep slopes a channel will, in attempting to reach a stable cross-section, tend to braid.

Experimental work, particularly by Schumm and Khan (1972) and Edgar (1974) has confirmed the influence of slope and also demonstrated that sediment transport rates, bed shear stress, mean velocity and width/depth ratio increased with slope and the change from meandering to braiding. In addition, examples exist in which a transition from meandering to braiding along a single stream is accompanied by an increase in slope (Leopold and Wolman, 1957).

Lane (1957) also proposed that excessive sediment load (*i.e.* an aggradational environment) could also produce braiding. Sediment size also plays a role and the proportionality:

$$Q_s d \propto Q_w s \qquad \text{(Schumm, 1968)} \qquad (5)$$

serves to illustrate the influence of sediment load and size on channel slope. Schumm (1968) also proposed the relationship:

$$Q_s \propto \frac{wls}{P} \qquad (6)$$

which shows an increase in slope and width with increasing sediment load along with an increase in bend wavelength and a decrease in sinuosity.

2.6.5.2 *Channel width.* Excessive channel widening seems to be central to the explanation of braiding. Recent work has made it increasingly clear that an unstable increase in channel width is responsible for the division of a channel. Sundborg (1956), Lane (1957), Schumm (1963) and more recently Pickup (1976) and Kirkby (1976)

have all shown that a relatively wide, flat bed (*i.e.* with maximum shear stress on the bed) is the most common and efficient shape for a stream channel carrying the majority of its sediment as bedload. Channel slope, bank erodibility and the type of sediment are also involved in producing channels with high width/depth ratios. Following Henderson (1961, 1966), Stebbings (1964), Yang (1971), Shen and Vedula (1969) and Church and Gilbert (1975), it is possible to show that a steeper channel slope (for whatever reason) tends to lead to high velocities, higher shear stress on the banks and, therefore, an increase in width. If the banks are relatively easily eroded then width may increase to a point at which depth and then bed shear stress are reduced. This will lead to deposition of the coarsest part of the load towards the centre of the channel and may ultimately produce flow division. Alternatively, as suggested by Church and Gilbert (1975), at high flow the channel may adapt to the water and sediment load imposed upon it by selectively scouring at certain points in the channel to create a deeper, narrower channel capable of sustaining higher velocities. Wilson (1973) proposed that as channel width increases, a series of secondary flow cells are set up which produce movement of bedload in such a fashion as to ultimately produce channel division. However, the mechanism involved here is a little difficult to envisage and its competency to produce channel division is questionable (Hey and Thorne, 1975).

The width/depth ratio also provides the basis of theoretical studies of channel stability by Engelund and Skovgaard (1971) and Parker (1976) which predict the existence of braiding beyond a certain channel width and may also predict the number of braids to be expected.

2.6.5.3 *Bank erodibility*. The role of bank erodibility is

difficult to evaluate because it is tied up in the other factors contributing to channel width. Brice (1961) maintained that slope alone would not account for braiding and that sediment factors, particularly bank erodibility, should also be considered. Mackin (1956) quoted an example of channel pattern change from meandering to braiding along a single stream for which the only available explanation was a change in bank material and its erodibility. The presence of gravel-bedded meandering streams with cohesive banks and sedimentary features similar to braiding (McGowan and Garner, 1970; Bluck, 1976) suggest that bank erodibility may indeed limit the development of braiding in some instances.

2.6.5.4 *Discharge variability.* High variability in discharge has already been discussed in relation to braided streams but some authors, especially Doeglas (1951, 1962) and Gupta (1975), have emphasized its importance as a cause of braiding. The evidence available is limited and contradictory, and it is not obvious how rapid discharge fluctuations alone could produce braiding. It cannot account for changes in pattern over short distances within a single stream and it is interesting that flume studies run at constant discharge Friedkin 1945; Leopold and Wolman 1957; Stebbings, 1964; Wolman and Brush, 1961; Schumm and Khan, 1972) have all been able to produce satisfactory braided patterns. In all probability, wide variability of discharge plays only a minor role in producing braiding.

2.7 Conclusions

While a large amount of information on certain aspects of braiding is available, there is still an obvious lack of data concerning

the details of the braided river processes and the causes of braiding. Much of the hydraulic data and information on bar formation comes from a very small number of studies and only one attempt has been made to pool the available information to characterize and explain the behaviour of certain braided rivers (Church and Gilbert, 1975). The use of a model, if reliable, may help to make available some of this information more readily than from the field and cover a wider range of conditions of sediment size, slope and discharge.

CHAPTER 3. MODELLING PRINCIPLES, EXPERIMENTAL PROCEDURE AND DATA COLLECTION

3.1 Introduction - Hardware modelling in geomorphology.

In 1967, Chorley (p. 63) commented that, "it is a constant source of surprise that hardware models have not hitherto proved to be of greater value in geomorphic research." Perhaps in response to Chorley's remark the use of modelling has played an important part in geomorphology over the last decade. This may also be attributed to an increasing emphasis on the study of landforming processes. Recently, Mosley and Zimpfer (1978), evaluating the contribution of hardware models, identified several advantages in their use:

(1) "They permit the identification, isolation, manipulation and precise measurement under controlled conditions of processes and variables that, for one reason or another, cannot be investigated in the field.

(2) They permit the study of evolving geomorphic systems, of the differences between equilibrium and non-equilibrium systems and of the implications of stage of evolution on the distribution of energy and matter within the system.

(3) They allow several processes or aspects of the landscape to be examined in a single study.

(4) They permit the study of various boundary and initial conditions.

(5) Careful observation of hardware models may reveal hitherto unsuspected phenomena and open new lines of enquiry.

(6) They provide easy visualization of geomorphic phenomena and thereby aid understanding and education." (Mosley and Zimpfer, 1978, p. 457).

In other words they may be a useful stimulus for theory which may be later tested in the field. However, Mosley and Zimpfer (1978) are also careful to point out some drawbacks to their use which, apart from the problems of a more practical kind, can be considered to be:

(1) "Initial and boundary conditions in the model may not be analagous to those in nature, or may influence model behaviour to an indeterminate or undesirable extent.

(2) Materials and processes in the model may be dissimilar to those in nature, and there may be no obvious way of relating model behaviour (*e.g.* rate of evolution) to that of the prototype. In particular, it is difficult to relate model behaviour under constant rates of operation of processes (constant energy and material input) to prototype behaviour, where highly variable rates of operation of processes are usual.

(3) Study of only one or two processes or independent variables may mask interactions that occur in nature.

(4) As model size decreases, there is a trade-off between precision of measurement and observation, and accuracy of representation of the prototype (realism). Confidence in the model results may therefore decline.

(5) They cannot be the final step in the development of a theory." (Mosley and Zimpfer, 1979, p.457-458).

In fact, what in some cases may be regarded as a disadvantage may in others be an advantage, and *vice versa*.

One area in which much of the recent hardware model study has been concentrated is that of fluvial morphology. This may in part be attributable to the existence of a long history and well-developed modelling theory in hydraulic engineering. In terms of Chorley's (1967) classification these would be regarded as scale models although it is common for geomorphologists to prefer to regard their models as streams in their own right rather than models of a specific prototype (*i.e.* as portions of "unscaled reality" Chorley, (1967) . In fact, we are dealing with a continuum between the two and where the model sits depends largely on the viewpoint of the researcher and the aims of the research.

Strictly speaking, for engineering purposes a model needs to satisfy three conditions of similitude - geometric, kinematic and dynamic (Henderson, 1966, p.489, 490). That is the ratios of all homologous dimensions must be equal; the paths and patterns of motion in

the model must be geometrically similar to their equivalents in the prototype and the ratios of all homologous forces must be the same. What this amounts to is that if a certain type of force is effective in a certain flow situation, the appropriate dimensionless number (*e.g.* Froude, Reynolds) must have the same value in the model and prototype. In fact, because of the complexity of movable bed models in particular it is impossible to fulfil all these criteria simultaneously. Traditionally engineers have employed scale distortion and a certain amount of trial and error in order to obtain a model which is an accurate representation of the prototype. Movable bed models also present the problem that the time scales for fluid flow and sediment motion are not necessarily the same (Henderson, 1966, p. 498).

In view of these difficulties, and also because the geomorphologist is often concerned with more general problems of explaining interactions between variables rather than discovering how a certain reach of a particular river behaves under given circumstances, the tendency in geomorphology has been to follow Hooke's (1968) suggestion that a more general principle of similitude, "similarity of process" be employed. This requires that the model fulfils three conditions:

(1) Gross scaling relations should be met.

(2) The model should reproduce some morphologic characteristics of the prototype.

(3) The processes producing this characteristic in the model have the same effect in the prototype.

Such a model will be hydraulically similar to some general prototype and will allow conclusions about the operation of processes, the controlling variables and the resultant landform to be reached and

give order of magnitude indications of the rates of operation of processes. Thus, for example, Schumm and Khan (1972) were able to demonstrate the existence of thresholds in channel pattern related primarily to channel slope, but the application of these particular thresholds to the natural situation is difficult because of unknown scaling differences and because of the interference of other variables excluded from the model.

3.2 Previous Model Studies of Fluvial Morphology

The advantages of hardware models listed by Mosley and Zimpfer (1978) suggest several areas in which they can be used and in the case of fluvial morphology the types of problems tackled in previous model studies may be conveniently considered in three groups.

The first concerns their use in overcoming the problem of time in understanding landforms evolving over many years. By reducing the scale, the length of time needed for their evolution is accordingly reduced, so allowing at least a description of the events involved in their formation and speculations as to the result of changing a given variable or variables. Thus Lewis (1941) and Schumm and Parker (1973) have studied terrace formation as a response to base-level changes; Shepherd and Schumm (1972) have investigated the incision of channels in resistant material; and Hooke (1967) has modelled the development of alluvial fans (see also the alluvial fan studies cited by Schumm, 1977). This type of model, particularly those of drainage besins is subject to the greatest scale problems to the extent that processes and effects observed in the model may be completely overridden by other factors in the natural situation (Mosley and Zimpfer, 1978).

Useful information on general channel form and new ideas and hypotheses explaining form may be obtained from flume models. Experiments on channel pattern (*e.g.* Friedkin, 1945; Leopold and Wolman, 1957; Schumm and Khan, 1972; Edgar, 1973) have been used to suggest the existence of thresholds governing channel pattern and have yielded information on the relationships between discharge, sediment characteristics and channel form and dimensions (Wolman and Brush, 1961; Ackers, 1964; Ackers and Charlton, 1970a).

Finally, more detailed hydraulic problems such as flow in bends (Hooke, 1975) or the form of scour holes at channel junctions (Mosley, 1976) can be better instrumented in the laboratory and the variables considered important can be manipulated separately to allow an examination of the influence of each alone.

3.3 Modelling Procedure

3.3.1 Principles of hydraulic modelling.

It has already been mentioned that the basic principle of hydraulic modelling is that the dimensionless numbers appropriate for a given flow situation have the same value in the prototype and model. In open channel flow the single most important such relationship involves the gravitational constant and gives the Froude number. In its basic form the Froude number is an expression of the ratio of inertia force to gravitational force ($\rho L^2 V^2 / \rho g L^3$) By cancelling out the common weight and characteristic length terms we arrive at the usual form of the Froude number = $V/\sqrt{gL}$.

The second important relationship describes the ratio of inertia force to viscous force and is termed the Reynolds number. The general expression for the Reynolds number is $Re = \frac{VL}{\nu}$. The values used for V and L vary with this type of Reynolds number. In open

channel flow V and L are mean velocity and depth of flow and the Reynolds number defines whether the flow is laminar or turbulent, the transition occurring at Re ≈ 500. Of particular concern in modelling is the grain Reynolds number $Re_* = \frac{u^* d_{90}}{\nu}$ which is important in the Shields' criterion for incipient motion. It is impossible to keep Reynolds numbers identical in prototype and model but it is possible to keep them sufficiently high to ensure that flow is fully turbulent and thus keep viscous scale effects very low.

One further effect of importance is that of surface tension. In prototype situations surface tension effects are negligible except close to solid boundaries. The only precaution which can be taken in models is to keep flow as deep and as wide as possible.

One further problem present in movable bed models is that the low water velocities may be incapable of moving natural sand and material with a lower density may be needed. Alternatively movement may occur but at higher Froude numbers than in the prototype. A calculation of the probable shear stresses in the model will serve to establish whether bed material motion can be expected in the model. The bed material must be of approximately the same shape and size gradation as the prototype. In fact, the choice of bed material size often determines the other model scaling criteria.

3.3.2 Modelling criteria for gravel braided streams. The modelling of sand bed rivers presents difficulties because of the tendency for model sediment of a suitable size to be cohesive and because the satisfaction of the Reynolds criterion (see below) is more difficult particularly as small ripples are commonly found in models using fine sand. Modelling of gravel can be achieved with non-cohesive sand

and is, therefore, relatively problem free. For this reason this study is concerned with gravel braided streams and, in view of the differences between sand and gravel rivers discussed in the previous chapter, application of the results is limited to gravel rivers.

Assume any prototype length L_p is reduced to a model length L_m. This ratio L_p/L_m is the scale ratio or length ratio L_r. From this the following criteria must be satisfied. Firstly, geometric similarity must be obeyed in all length parameters, *i.e.* L_r must be the same for all equivalent lengths. Notice that variables such as slope and relative roughness (D/d_{90}) remain the same because they are dimensionless (L/L). Secondly, the Froude number must be the same in model and prototype and, in fact, it can be demonstrated that this must follow from geometric similarity. This follows from an empirical friction law for the velocity distribution such as:

$$\frac{\bar{v}}{u*} = 2.5\ln\left(\frac{11D}{d_{90}}\right) \qquad \text{where } u_* = \sqrt{gDS}$$

$$\text{if } 2.5\ln\left(\frac{11D}{d_{90}}\right) = K$$

$$\text{then } \bar{v}^2 = u_*^2K^2$$

$$\frac{\bar{v}_p^2}{\bar{v}_m^2} = \frac{g\ D_p\ S}{g\ D_m\ S} \tag{7}$$

$$\bar{v}_p^2 = \bar{v}_m^2\,\frac{D_p}{D_m}$$

From the Froude relationships $\dfrac{\bar{v}_m^2}{g\ D_m} = \dfrac{\bar{v}_m^2\ \frac{D_p}{D_m}}{g\ D_p}$

which gives $\dfrac{D_p}{D_m} = \dfrac{D_p}{D_m}$ (Shaw and Parker pers. comm.)

Thus Froude similarity must follow from geometric similarity.

The specific gravity and gradation of the model and prototype bed material must be the same. Finally, the particle Reynolds number must exceed that necessary to ensure rough flow, *i.e.* about 50. In fact,

values as low as $R_e* = 20$ may produce viscous scale effects (*i.e.* distortion due to a high viscosity) of only 10 or 15 percent (Parker, pers. comm.).

Given these criteria and due to Froude similarity, the following scale ratios result:

Velocity $V_r = L_r^{0.5}$

Time $T_r = L_r V_r^{-1} = L_r^{0.5}$

Discharge $Q_r = V_r L_r^2 = L_r^{5/2}$

Discharge per unit width $q_r = V_r L_r = L_r^{3/2}$

In the modelling of gravel braided streams one further piece of information may be useful. Studies of full-scale and laboratory streams illustrate the probable existence of a threshold between meandering and braiding based primarily on slope. Parker and Anderson (1975) suggested that when geometric and Froude similarity obtain then order-of-magnitude similarity of the factors governing the existence, or otherwise, of braiding also obtain provided some sediment transport exists. The fundamental relationship here is that for braiding to occur the inequality $D/W \leq S/Fr$ must be obeyed. Thus once the values of the relevant variables are known it is possible to predict whether braiding will occur.

Given the limitations on size imposed by the equipment available, and working from an imaginary prototype based on published data on gravel braided streams with a model scale of 100, we can estimate the values of the relevant parameters as follows:

<u>Prototype</u> $d_{50} = 0.1$ m

$d_{90} = 0.2$ m

$W \quad = 150$ m

$D \quad = 1$ m

$S \quad = 10^{-2}$

From the friction law $\frac{\bar{v}}{u_*} = 2.5 \ln (\frac{11D}{d_{90}})$

$V_p = 3.14$ m/s

$q_p = 3.14$ m/s

The Shields stress $t^* = \frac{DS}{1.65\ d_{50}} = \frac{1x0.01}{1.65x0.1} = 0.61$

which exceeds the critical Shields stress for large particles.

$Re_* - \frac{u_*\ d_{90}}{\nu} = \frac{\sqrt{(9.81x10x0.01)}x0.2}{10^{-6}} = 6.26x10^4$ at 20°C

<u>Model</u> $\quad d_{50} = 0.001$ m

$d_{90} = 0.002$ m

$B \quad = 1.5$ m

$D \quad = 0.01$ m

$S \quad = 10^{-2}$ *i.e.* remains unaltered

From relations (8)

$\bar{v}_m = 0.314$ m/s

$q_m = 3.14 \times 10^{-3}$ m^2/s

Shield's stresses are dimensionless and therefore remain unaltered.

$Re_* = \frac{\sqrt{(9.81x0.01x0.01)}0.002}{10^{-6}} = 62.6$ at 20°C

Then Q = 4.7 litres/S

This gives us an order of magnitude impression of the grain size and discharge to be used, indicates whether we can expect sediment motion under these conditions and establishes whether the particle Reynolds number corresponds to fully turbulent flow.

In fact, it is possible to reverse the whole process and, given a model which is dynamically and geometrically correct, the dimensions

can be extrapolated to allow comparison with a given natural stream.

By devising a series of dimensionless parameters for channel dimensions it is possible to compare model and full-scale channel data directly by plotting them on the same graph (see for example, Ackers and Charlton, 1970b).

It should be realized, however, that the simultaneous exact modelling of fluvial processes of sediment transport, flow resistance and bank stability is impossible because a complete set of parameters has yet to be defined. It is hoped that by obeying gross scaling procedures some of the details of the modelling will in effect take care of themselves and at least give approximate similarity of process even if details such as rate of sediment transport are not exactly scaled. The comparability of model features and full-scale features will be discussed later.

3.4 The Model and Experimental Equipment

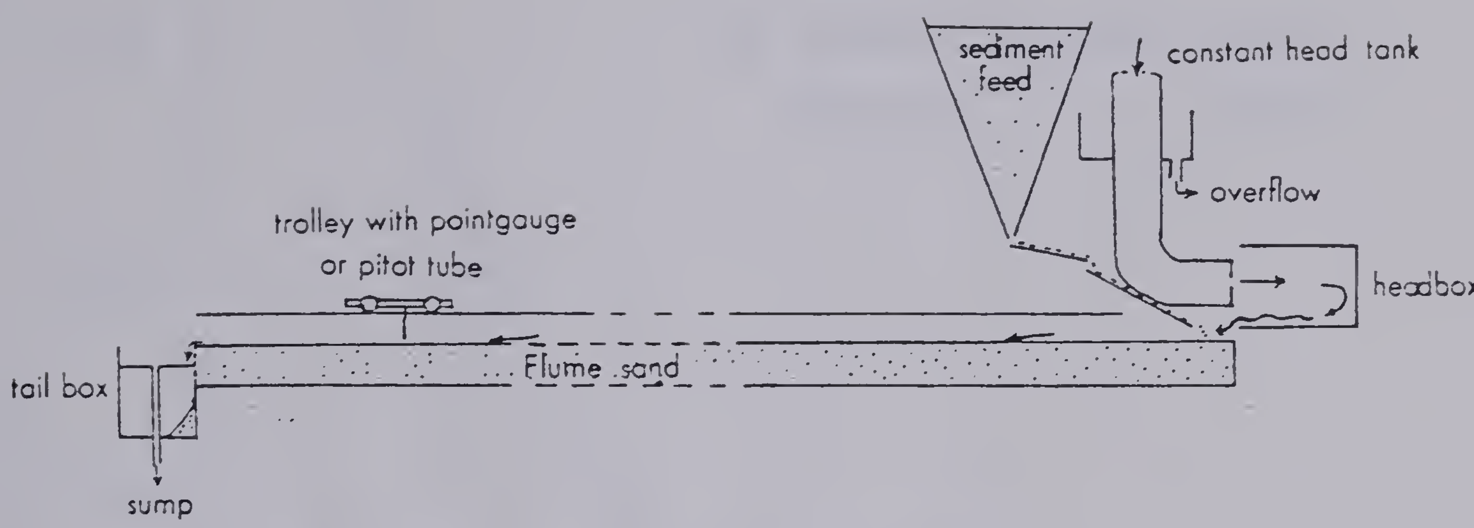
The experiments were carried out in a river tray 9 m long by 1.3 m wide, equipped with a jack to adjust the slope. The flume was of a non-recirculating type, water being fed from the city supply and leaving through a tail box into a sump. Discharge was controlled by a constant head tank which could be varied in elevation. Due to a series of expansions and contractions inside the tank, the standard relationship between head and velocity ($V = \sqrt{2gh}$) could not be relied on for calibration so this was done independently using a large calibrated container. The weight of water discharged into this container over one minute was measured for a series of head settings and a rating curve established from these values. In the event only one discharge was used

throughout the experiment. The water jet from the head tank discharged up-flume into a box from which it entered the head of the flume over the lip of the box (see Fig. 3.1). Although crude, this arrangement proved satisfactory for this type of study but more refinement, particularly in introducing the water to the channel, is desirable.

Where the flow entered the flume, dry sediment was fed from a Syntron sediment feed consisting essentially of a large hopper with a vibrating feed slot at the base. The sidement feed rate could be varied but calibration of the device proved problematical because of the dependence of the feed rate on the level of sediment in the hopper. Therefore, an effort was made to ensure that the hopper was continually topped-up and the feed rate was checked regularly and frequently to keep it as constant as possible. Sediment leaving the end of the flume was deposited in the tail box from which it was removed regularly, measured and dried for return to the head of the flume. The grain size distribution of a sample of the industrial sand used, along with the relevant descriptive statistics, are displayed in Fig. 3.2. The sand is well sorted with a total range covering only slightly more than one phi unit (1-2 mm) and this is lower than the size range of fluvial gravel (*e.g.* Smith, 1974). The grains are generally well-rounded and ellipsoidal in shape.

Throughout the experiment the discharge and sediment feed rate were kept constant. A suitable feed rate was arrived at after a period of time during which the amount of sediment collected in the tail box was monitored and during which time the river itself was monitored for changes in average elevation and slope. The aim was to achieve and maintain a balance in feed rate and collection rate which produced no

Figure 3.1 Diagram of flume equipment and view of flume looking upstream.


sediment feed
constant head tank
overflow
trolley with pointgauge or pitot tube
headbox
tail box
Flume sand
sump

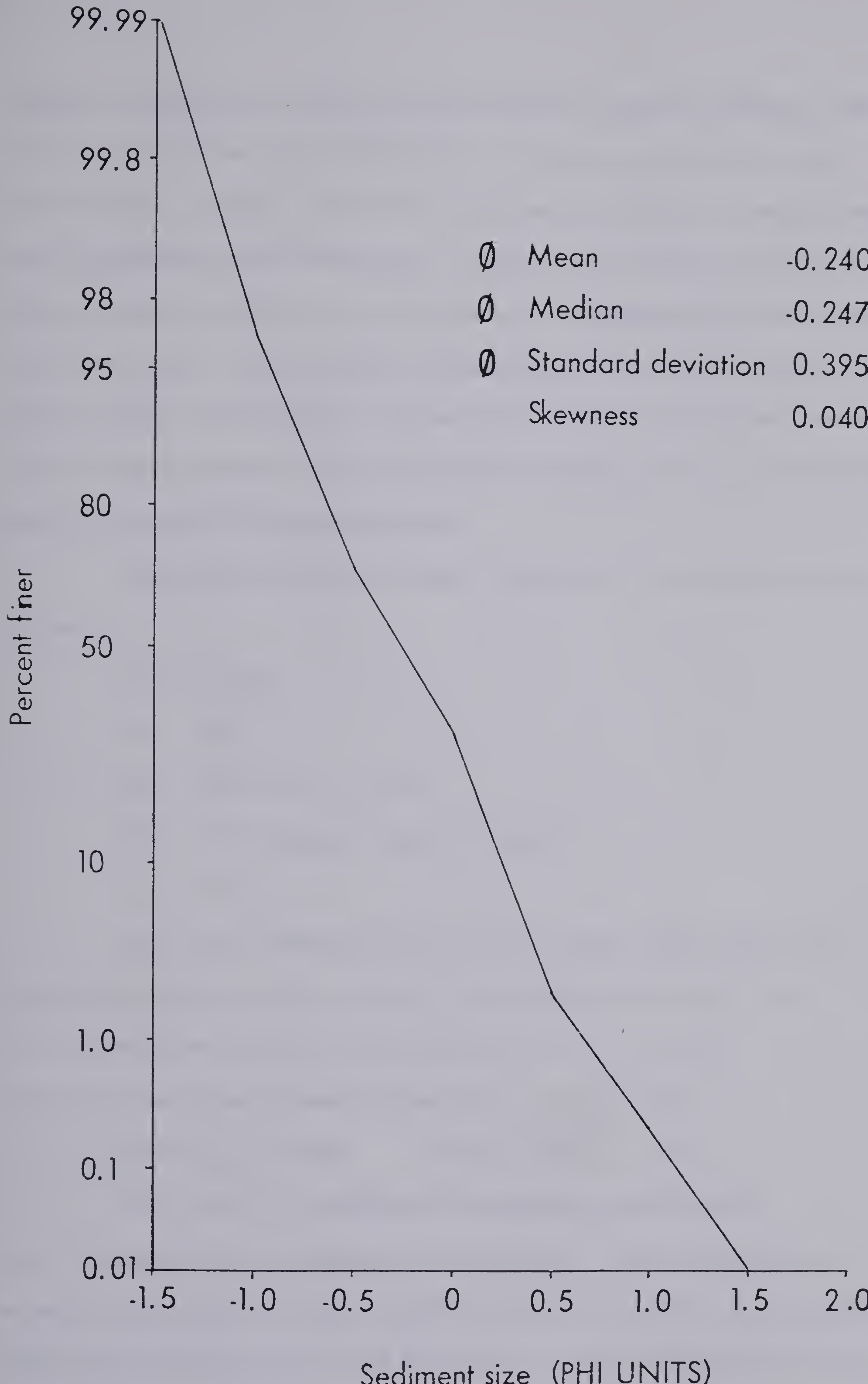


Figure 3.2 Size gradation of sand used in flume.

change in elevation or slope in which case it could be assumed that the river was in approximate equilibrium. Once the correct rate was established a careful check of the sediment balance was kept to ensure that equilibrium was maintained. In fact, the sediment collection rate was never constant so that it was necessary to average measurements over a number of hours. After running the experiment for several months, the channel slope was checked at the conclusion of the experiment and was found to have deviated little from the original, apart from the development of a slightly concave profile.

The values of the relevant variables in the model were as follows:

$Q = 1.1$ L/s

$S = 0.013$

$Q_S = 0.01$ L/s or 1.7 g/s

$W = 1.3$ m (overall width of flume)

$D \simeq 0.01$ m

The water temperature was always warmer than about 12°C which gives values of Re* - 60 at 1 cm depth, and 45 at 0.5 cm. Given these dimensions and given that many of the model channels show Froude numbers close to 1, we arrive at:

$$D/W = \frac{1}{130} = 0.007 \qquad S/Fr = \frac{0.013}{1} = 0.013$$

$D/B < S/Fr$ - therefore the channel should braid.

3.4.1 Measurement of topography and velocity. Bed topography was surveyed using a point gauge mounted on a trolley which straddled the flume and could be moved along the flume on rails which served as a sloping datum. The rails were levelled to a slope of approximately 0.013. Scales along the flume, across the trolley and on the vertical

shaft of the point gauge gave a 3-dimensional coordinate system on which all measurements could be based.

Wherever possible (*i.e.* where flow was deep enough) velocity measurements were made with a pitot tube which could be mounted on the trolley. The pitot tube makes use of the Bernoulli principle which can be expressed as $p + \frac{\rho v^2}{2}$ = constant. In other words, there is an inverse relationship between fluid pressure and fluid velocity along any streamline (assuming flow is steady and incompressible). Any decrease in velocity will cause a corresponding increase in pressure. If any object is placed in the flow the velocity on the upstream side of the object will be zero, pressure will be at a maximum and will increase as the square of the velocity along the streamline upstream of the obstruction. This can be recorded as a difference between the hydrostatic pressure and the dynamic fluid pressure. The pitot tube measures both the dynamic pressure parallel to the streamlines and the hydrostatic head and from this a velocity can be calculated. Essentially the pitot tube consists of two L tubes (usually one inside the other). The inner tube has one opening directed upstream to record the dynamic fluid pressure while the outer tube has several apertures arranged at regular intervals around the circumference of the tube to record the hydrostatic pressure. By connecting the two fluid-filled tubes to a pressure transducer the difference in head can be measured. The transducer gives a voltage reading which can be converted to a velocity by the relation $u = 0.732 \sqrt{\text{volts}}$. The value of the constant (in this case 0.732) will depend on the calibration of the transducer. The calibration is obtained by imposing a known difference in head on the system from two containers of water mounted on a stand connected to

opposite sides of the pressure transducer, and then adjusting the transducer reading to make 1 volt equal to a difference in head of 1/10". Because of the effect on the readings of air in the tubes and because of a tendency for the calibration to drift slightly, the equipment was checked and calibrated before and after each series of measurements.

Where the flow was less than about 0.5 cm deep the pitot tube with an outside diameter of 0.26 cm (1/8") could not be used and in these areas it was necessary to rely on the timing of floats using a stop clock. The conversion of these to average velocities is discussed below (section 3.5.3).

3.5 Experimental Procedure and Data Collection

The river was self-formed. The experiment was started from a straight channel 1 cm deep by 25 cm wide with a flat bed and concave upwards banks cut down the centre of the flume. The sand was gradually soaked and then the discharge increased to the required level. This one stream was used throughout the experiment but the flow was turned on and off repeatedly with only minor alteration of the features formed at high flow (*e.g.* dissection of bar margins and slight refilling of scour pools).

3.5.1 Sediment sampling and analysis. The grain size data used in the study consists of a series of samples used to obtain roughness data for channels and to investigate the sorting of sediment over the depositional surface. The samples analyzed consisted of:

1) samples of bed material from 34 active channels,
2) eight pairs of samples from the upstream ends and downstream margins of transverse bars,
3) five pairs of samples from scour pools and channels

immediately downstream,

and 4) miscellaneous samples to illustrate other aspects of sorting such as vertical changes within a single bar and avalanche face, lateral sorting on bars and downstream of pools and sorting associated with channel division and abandonment.

Because the grains sampled were so small and because they were taken largely under water the most effective way of collecting samples was with a small bedload type sampler (Fig. 3.3). By running the sampler along the bed surface a bulk sample of the surface layers could be collected in the mesh attached to the back of the sampler. As a means of measuring bedload this device is unreliable but was adequate for collecting a representative sample for use in a size analysis.

The grain size distribution is based on the measurement of individual grains under a microscope using a micrometer slide and calibrated eyepiece. The projected long (a) and intermediate (b) axes were measured to within 0.025 mm. Provided the grains lie with their short (c) axes normal to the slide surface, these projected axes correspond to the actual a and b axes. Obviously some error will be introduced here because the tilt of the c axes is unknown but it is unlikely that a tilt of a few degrees will have a great influence on the visible grain dimensions. All the samples are subject to the same error (assuming they contain the same range of grain shapes) so as long as comparisons are confined to the flume samples this error is not serious. For each sample approximately 100 grains were measured (large samples were progressively broken down to give 100 grains) and the b

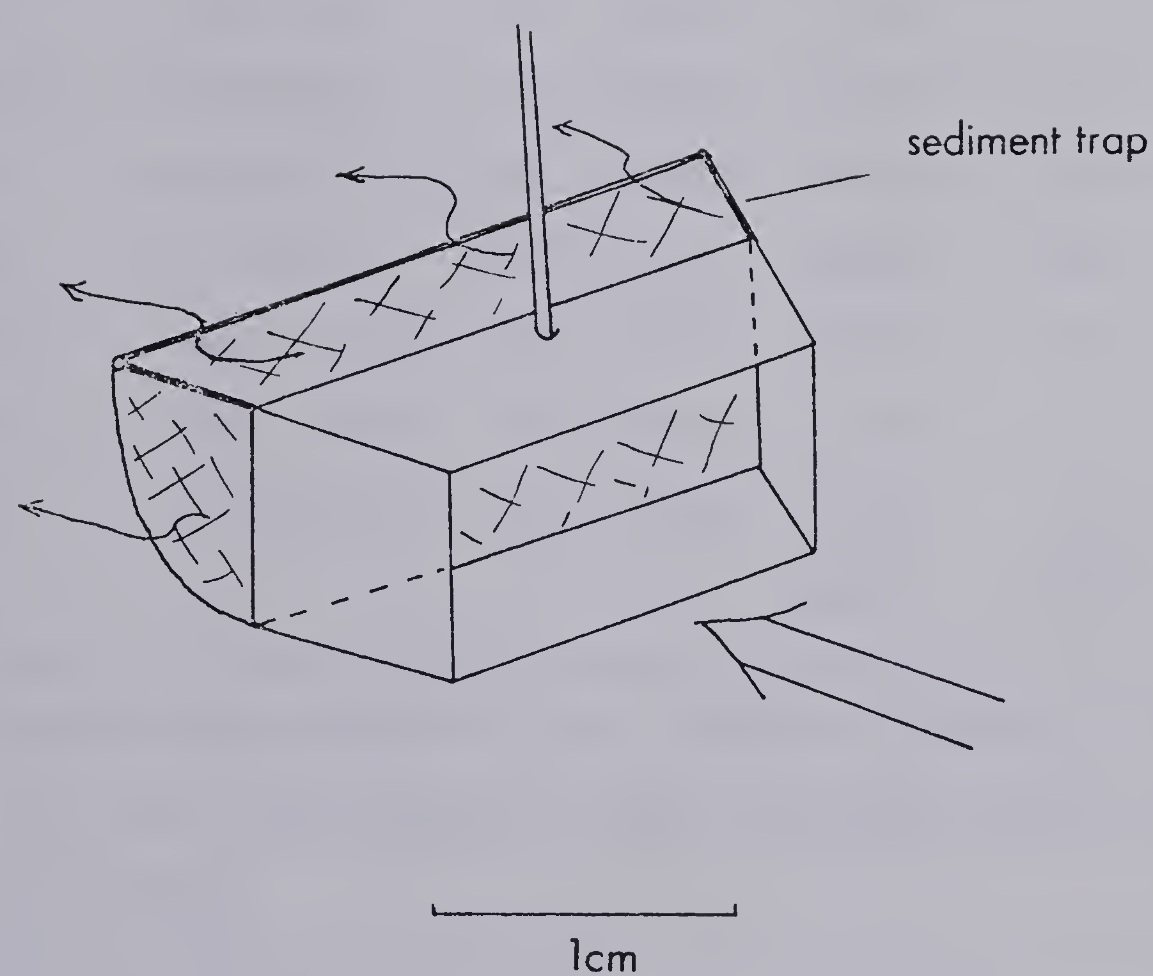


Figure 3.3 Sketch of bed material trap.

axes were tallied into ¼ Ø classes. This gives a frequency distribution by number and in order to make the distribution equivalent to a sieve sample (*i.e.* a distribution by weight) it is necessary to multiply each grain size by d^3 where d is the intermediate (*b*) diameter (Kellerhals and Bray, 1971). To convert individual grain dimensions would be time consuming so the procedure employed was to multiply the frequency in each class by the cube of the average diameter of that class (in mm). An example is given below:

Size Range (mm)	Ø	fn	d^3	fw(fnxd^3)	%
0.595 - 0.707	0.75 - 0.5	4	0.272	1.09	.9
0.708 - 0.841	0.5 - 0.25	15	0.465	6.97	6.1
0.842 - 1.00	0.25 - 0	26	0.781	20.31	17.6
1.01 - 1.185	0 - -0.25	37	1.322	48.91	42.5
1.186 - 1.416	-0.25 - -0.5	11	2.202	24.22	21.0
1.417 - 1.678	-0.5 - -0.75	2	3.706	7.41	6.4
1.679 - 2.00	-0.75 - -1.0	1	6.224	6.22	5.4
				115.13	99.9

Cumulative percentages were then plotted on probability paper and $\varnothing_5$, $\varnothing_{16}$, $\varnothing_{50}$, $\varnothing_{84}$, $\varnothing_{95}$ obtained in order to calculate the Folk and Ward (1957) statistics:

$$\text{Mean, } M_Z = (\varnothing_{16} + \varnothing_{50} + \varnothing_{84})/3$$

$$\text{Sorting, } \sigma = (\varnothing_{84} - \varnothing_{16})/4 + (\varnothing_{95} - \varnothing_5)/6.6 \qquad (9)$$

$$\text{Skewness, } \alpha = \frac{(\varnothing_{16} + \varnothing_{84}) - 2\varnothing_{50}}{2(\varnothing_{84} - \varnothing_{16})} + \frac{(\varnothing_5 + \varnothing_{95}) - 2\varnothing_{50}}{2(\varnothing_{95} - \varnothing_5)}$$

The conversion to distribution by weight should not be regarded as producing an exact equivalent to a sieve distribution. Sahu (1964) has pointed out some of the errors involved as a result of

differences between actual and projected *b* axes, irregular grain shapes, error in the use of the conversion d^3 which depends on the shape of grains and the assumption that the specific weight of all grains is the same. Thus, again, it should be emphasized that the distributions obtained are only a type of distribution by weight which bear a close but unknown (and probably variable) relation to a sieve curve. The errors should be approximately the same for all the flume samples because they are drawn from the same basic population, however, only general differences and trends can be compared with data from full-size rivers.

3.5.2 <u>Channel geometry</u>. In order to establish a hydraulic geometry for the braided anabranches a series of channel cross-sections (34 in total) were measured to obtain the relevant parameters - width, depth, cross-section area, slope, mean velocity, discharge and active width. This requires that the channels measured be comparatively stable, *i.e.* show no aggradation, degradation or bank erosion. This is in conflict with the natural instability of braided river channels. About twenty minutes in which little change occurred was needed in order to complete the measurement of each channel. Not surprisingly such conditions were rare. In addition to the stability criterion the channel reaches also had to be fairly straight, free from the influence of the flume walls and have a large proportion of the bed (80 percent or more) showing active sediment transport. Under experimental conditions it is much easier to pick out suitable channels and check them to ensure that they comply with these criteria than is the case in the field, but the rapidity of change which is so useful in some respects makes these kind of measurements rather frustrating. However, it is evident that similar

measurements in the field are fraught with much greater problems and possible errors (Fahnestock, 1963).

The procedure for data collection, once a suitable reach had been identified, was to mark the cross-section perpendicular to the flow using a section of metal tape measure mounted on a stiff wire spanning the channel and planted in the bed at either end. The pitot tube was then positioned in the line of the cross-section to measure both velocity and channel dimensions. At each vertical the depth was established using a piece of fine wire mounted above the horizontal portion of the pitot tube to give a water surface elevation and then lowering the tube so that its lower surface just touched the bed. By knowing these two elevations and the distance between the bottom of the tube and the end of the wire the depth could be quickly calculated and the pitot tube raised to 0.6 of the water depth (measured from the surface) to measure the average velocity. The accuracy of this measurement depends on the form of the velocity profile. Ideally two or three velocity measurements in each vertical are desirable but time allowed for only one. After allowing a minute for the tube to adjust to the new velocity a voltage reading was taken. Generally the voltage fluctuated over a range of 0.4-0.5 volts but by keeping a careful check it was possible to pick out a representative value from the middle of the range observed over one minute. The use of a capacitor helped to damp the fluctuations although it lengthened the response time. The velocity is a function of the square root of the voltage so that over the range measured a given voltage fluctuation represents a different velocity fluctuation but in fact over most of the range (1.5-2.5 volts) this difference is not great and a difference in voltage of 0.1 volts is

closely equivalent to a velocity of about 1 cm/s, *i.e.* less than 5 percent in most cases. The depth and velocity measurements were repeated for at least 5 regularly spaced verticals in each cross-section, giving a spacing of 2 or 3 cm depending on the channel width. Width was taken from the tape measure. Discharge was calculated using the mid-section method (Gregory and Walling, 1973, p. 132). Given an error in depth of 5 percent (½ mm) in 1 cm and an error in width of less than 5 percent, it is reasonable to think that channel cross-section area and discharge measurements could be subject to a cumulative error of 10-15 percent.

Water surface slope in the reach was obtained from water elevations 10 cm up and downstream of the cross-sections using an average of 3 measurements across the channel in each case. Error arises here from the existence of transverse water slopes which should be accounted for by averaging 3 measurements across the channel and from ripples and standing waves on the surface which may reach an amplitude of 1 mm or more. Apparent slopes had to be converted to actual slopes by taking into account the fact that the measurements were taken from a sloping datum and from channels oblique to the flume walls in many cases.

3.5.3 Scour holes. The dimensions of scour holes were collected with the intention of deriving relations between these dimensions and possible controlling variables such as angle of incidence, and relative discharges of contributing channels. The scour holes are generally of a fairly complex form and the contributing channels are rarely stable enough or deep enough to make the gauging procedure described above possible. As a result, the amount and quality of the data obtained did not allow an analysis of the type originally envisaged.

The basic procedure involved the use of the point gauge to

measure the maximum depth (water surface to bed) of the pool, the width at this point and the length from the head to the point where the bed slope reversed. The angle of incidence of the two contributing channels was measured using a protractor with two pointers which could be rotated to run parallel with the main current in each channel. Channel dimensions were surveyed using the point gauge and average velocity was obtained using floats. Average velocities were each based on 5 measurements. The conversion of these float velocities to a mean velocity involves the use of a correction factor which usually lies in the range 0.8 to 0.9. The four velocity profiles measured gave values of the ratio of velocity at 0.6 depth to surface velocity in this range. As a check the float method was used on some of the stable channels for which pitot tube measurements were also available. The conversion factor for these channels ranged from 0.71 to 0.99 with an average of 0.85. Thus a value of 0.85 was used which may give an error of over 10 percent in some cases.

3.5.4 <u>Other data</u>. In addition, the point gauge was used to measure a variety of cross-sections and longitudinal profiles of scour holes, bars, channels and of the whole model river. A photographic record including time-lapse film of channel changes and bar formation was also obtained.

CHAPTER 4. DEVELOPMENT, CHARACTERISTICS AND PROCESSES OF THE BRAIDED RIVER MODEL

4.1 Introduction

If we are to fully understand geomorphological phenomena at a quantitative level it is essential that we first obtain a good qualitative familiarity with the processes involved. One of the problems in studying braiding has been the difficulty of observing the relevant processes and having to rely on what Lewin (1976b) referred to as "enlightened inferences as to the pattern of movement derived from observations of the sediment involved." Part of the motivation for a model study was to allow a more complete description of the behaviour of braided rivers and so give a more satisfactory starting point for quantitative studies. It is hoped that this chapter provides such a base.

4.2 Initiation and Evolution of the Braided Pattern

At the beginning of the experiment the flow completely filled the initial channel (*i.e.* to a depth of about 1.5 cm) and overtopped the banks slightly. It was immediately apparent that this channel was unstable and within a few minutes the bed began to show the first signs of the formation of a series of alternating bars. This occurred first at the head of the flume but within an hour the entire channel showed a sequence of alternating bars and scour holes and some minor bank erosion. The bars were lobate in form with well-defined avalanche faces on their downstream and channelward margins. Small inactive troughs developed between the bars and channel banks. The thalweg

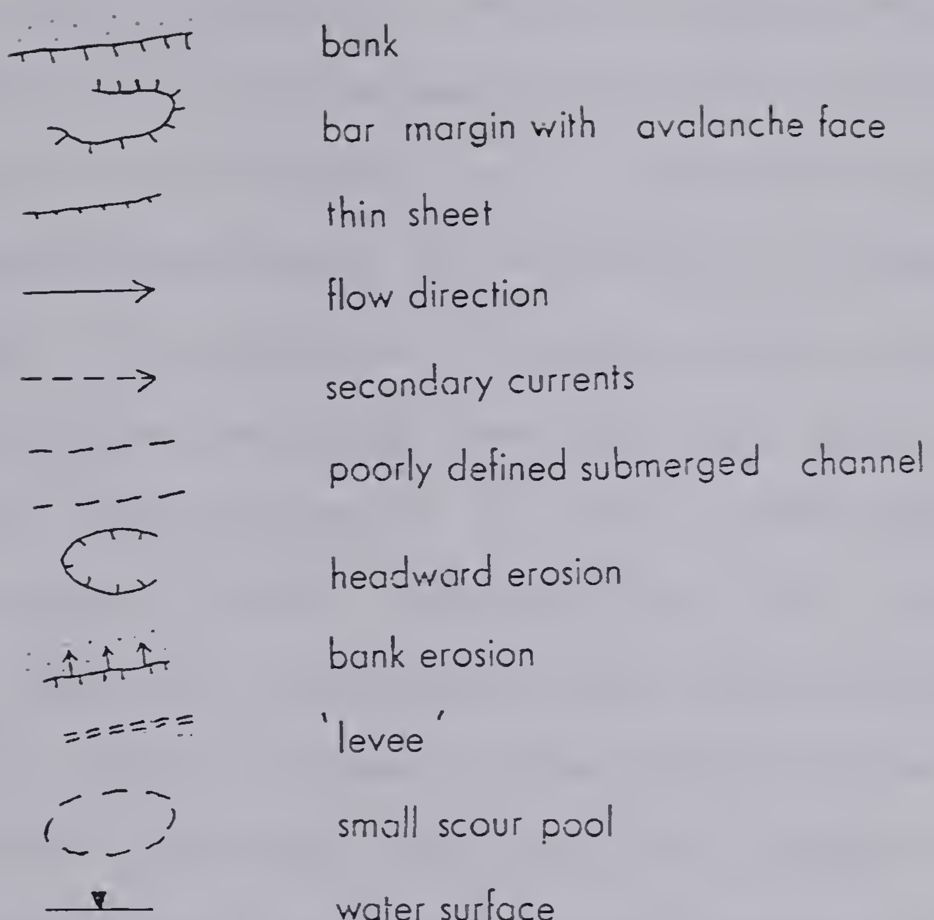
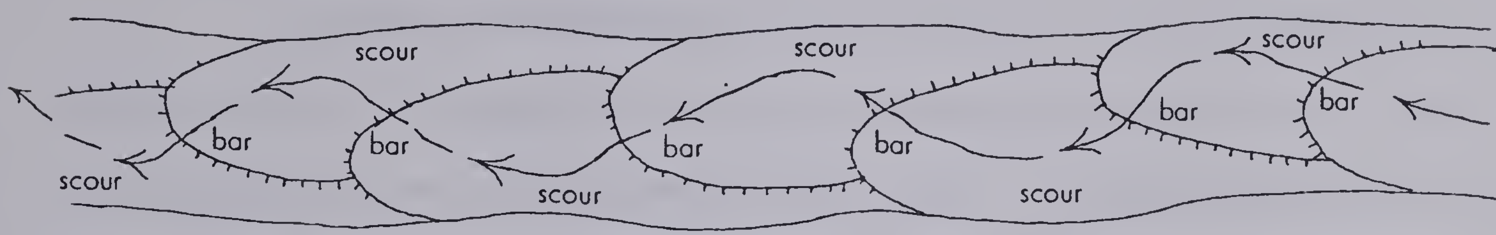


Figure 4.1 Key for sketches in Chapter Four.

meandered through this sequence of bars and scour holes. Bars were spaced very regularly, about 1 m apart at first, giving a meander wavelength of 2 m or 8 channel widths. Fig. 4.2 shows the alternating bars after 1 hour.

Several reports of similar features in flumes and natural rivers have been published. Wolman and Brush (1961) referred to these alternating bars as pseudomeanders and Hickin (1969, 1972) has given detailed accounts of their form and the hydraulic geometry of the associated channels along with descriptions of equivalent features in the field. The engineering literature contains several studies of alternating bars including those of Einstein and Li (1958), Einstein and Shen (1964) and Chang *et al.*, (1971). Model studies of channel pattern by Karcz (1971), Schumm and Khan (1972), Edgar (1973), and Parker (1976) all include descriptions and/or illustrations of alternating bars. Their occurrence in flume channels appears to be associated with fairly high slopes, width/depth ratios greater than about 12, and for natural materials, Froude numbers close to one (Wolman and Brush, 1961; Chang *et al.*, 1971). Einstein and Shen (1964) report similar occurrences in laboratory experiments by Vanoni and Brooks (1957) and Kinoshita (1956). Chang *et al.*, (1971), however, obtained a similar pattern at much lower Froude numbers with a bed material of plastic beads. This is to be expected because the less dense plastic requires lower velocities for its transport and for a given depth a lower velocity produces a lower Froude number. In natural channels meander initiation from straight channels often involves an alternating bar pattern (Keller, 1972; Lewin, 1976(a)). Karcz (1972) observed a very well defined pattern of alternating bars and scour holes in ephemeral stream

Figure 4.2 Channel pattern after one hour. Note distinct alternating bar pattern and sinuous thalweg.


scour
scour
scour
bar
bar
bar
bar
bar
bar
scour
scour
scour

beds in Israel. Observations by Schumm and Khan (1972) indicated that in the absence of very fine cohesive sediment and at a sufficiently steep slope (0.013-0.016), the alternating bar pattern may be modified to a fully braided pattern.

A complete discussion of the origin of the alternating bar pattern cannot be attempted here but a few brief comments will serve to indicate the sort of mechanisms involved. In 1958 Einstein and Li were able to show that secondary flow is to be expected in straight turbulent flow because of the tendency for lines of constant velocity to be parallel neither to themselves or the boundary. It has become increasingly prevalent to regard the formation of large scale channel features as being the result of the largest of a family of turbulent eddies present in a natural river channel whose dimensions are on a scale comparable with that of the cross-section of the flow. Thus, Einstein and Shen (1964) and Shen and Komura (1968) discussed such a mechanism and indicated the importance of channel roughness in generating such secondary flow elements. Yalin (1971) demonstrated that a systematic disturbance caused by the behaviour of these large eddies must result in the generation of identical disturbances alternating downstream and spaced at regular intervals. These velocity perturbations produce discontinuities in sediment transport and hence changes in bed elevation. In the case of meanders these fluctuations would occur at approximately $2\pi w$, $4\pi w$, $6\pi w$ ....

The alternating bar problem has also been approached via stability analyses (Anderson, 1967; Engelund and Skovgaard, 1973; Parker, 1976). These rely on the generation of systematic oscillations in the rate of sediment transport generated by oscillations in velocity

within the fluid rather than by random turbulence effects. If velocity and sediment transport oscillations are slightly out of phase then undulations will be generated which, rather than being damped out, will increase in amplitude. Once established, the bends produced by the alternating bars increased in amplitude through bank erosion and the channel width increased gradually (Fig. 4.3). Width increase tended to work upstream from the lower end of the flume. As width increased, depth decreased and the higher portions of the bed became inactive. Generally, the centre of the downstream margins of the bars were the first to show signs of abandonment and exposure. The flow was diverted to either side of these areas, reactivating the troughs arising from the original alternating bar pattern and producing new bar lobes, gradually complicating the pattern and exposing previously active portions of the bed (see Fig. 4.4). It is interesting in this context to note that Einstein and Shen (1964) found that an increase in the width/depth ratio of their flume channel produced a change from a single to a double diagonal bar pattern and Parker (1976) provided a theoretical analysis to show that an increase in width/depth ratio could lead to the development of multiple meandering tendencies within a single channel, *i.e.* braiding.

After four hours, the whole width of the flume had been reworked and a complex of bars and channels was evident. Generally, one major channel and a number of small channels occurred at any given cross-section. At this stage it became obvious that the width of the flume itself was a serious constraint on full pattern development but comparison of the flume features with natural rivers suggested that they were largely unaffected by this. Wherever channels

Figure 4.3 Channel pattern after two hours. Note sinuous channel.

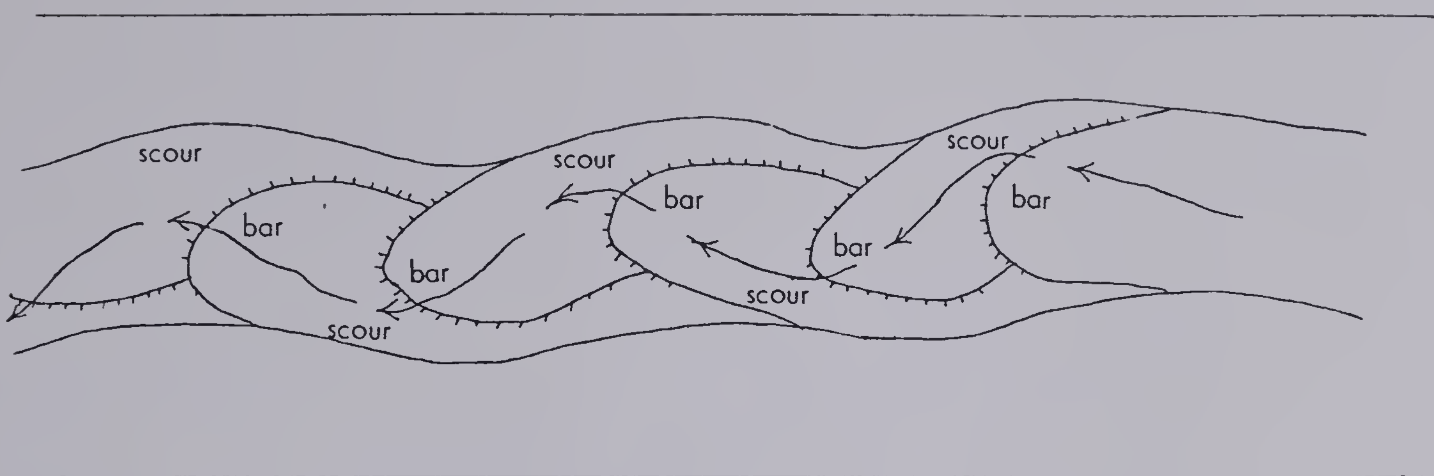
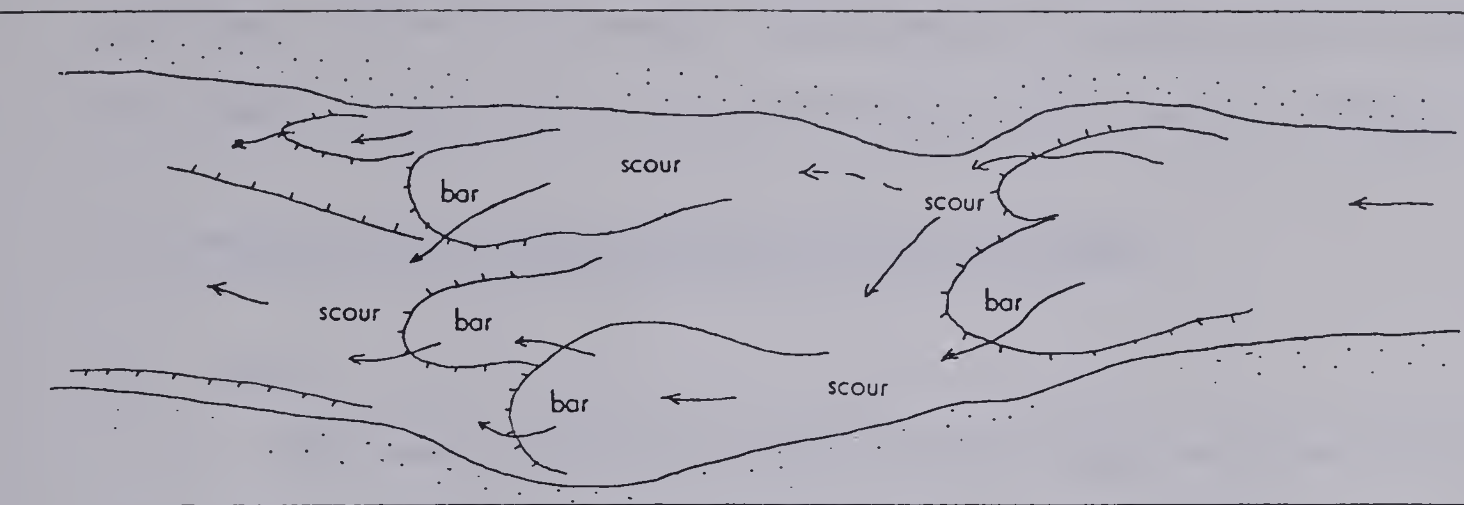

scour
bar
bar
scour
scour
bar
bar
scour
scour
bar

Figure 4.4 Channel pattern after four hours. Alternating bar pattern broken down to give braiding.


scour
bar
scour
scour
bar
bar
bar
scour

came into contact with the flume walls large scour holes developed with deposition immediately downstream. At times such features exerted a significant influence on events downstream but the descriptions which follow deal entirely with developments free of this wall influence.

4.3 Features of the Fully Developed Braided Pattern

4.3.1 Bars

The types of bars considered at this stage are essentially variations of the alternate type involved in the original pattern development. They show a lobate form with or without a well-defined avalanche face, vary in thickness from a few grains to 1 or 2 cm, are all dynamic features controlled by and in turn influencing the flow, and commonly serve as important transportation surfaces for bedload because they occupy a large portion of the channel width when active. Good field descriptions of the form of these features are few but Hein (1974) and Smith, N.D. (1974) have described some of their characteristics from gravel braided rivers while Collinson (1970) and Cant and Walker (1978) provided good illustrations of similar forms in the sandy Tana and South Saskatchewan rivers respectively. McGowan and Garner (1970) and Gustavson (1978) described such features from the point bars of meandering gravel-bed rivers, while Rust (1972) suggested their importance in the sedimentology of the braided Donjek River. In addition, Boothroyd and Ashley (1975) provided good illustrations of such features but apparently failed to recognize their significance.

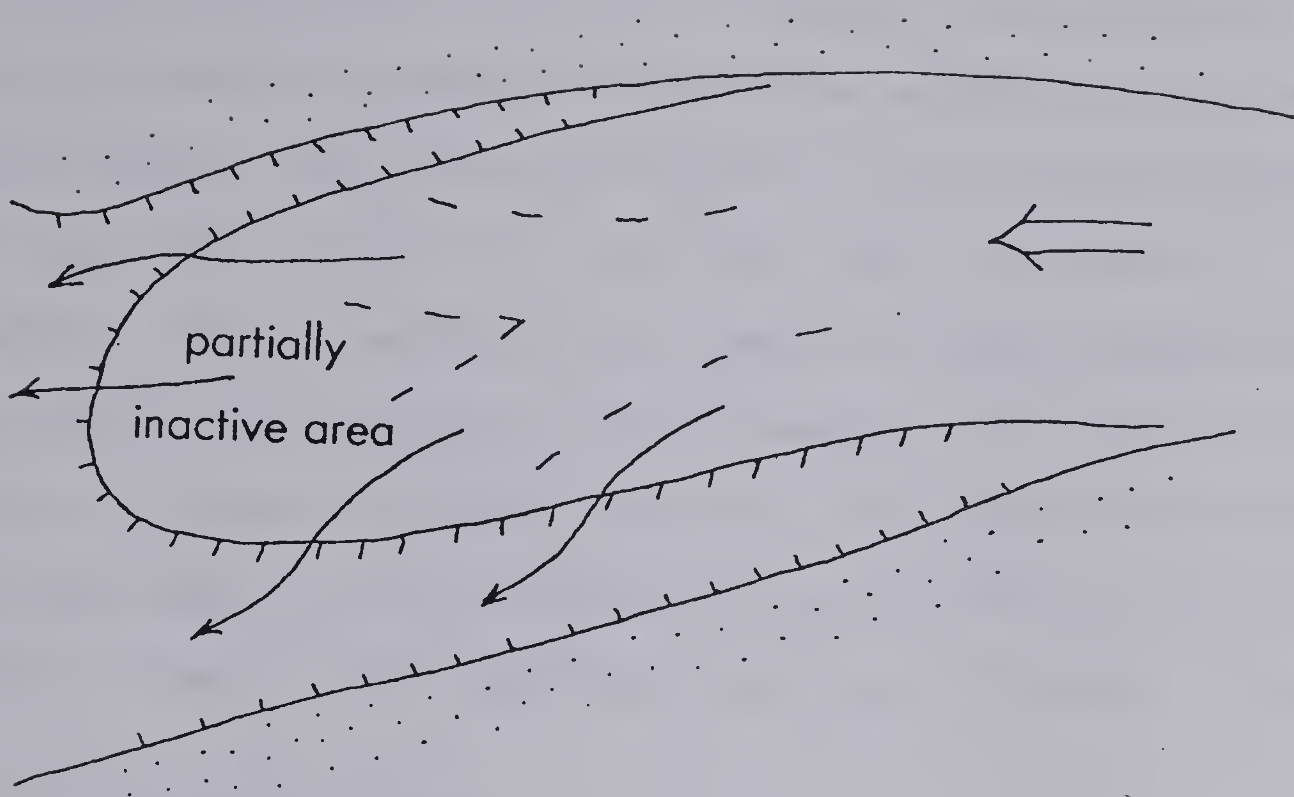
These features are apparently equivalent to the transverse and diagonal unit bars of Smith, N.D. (1974). While their formation can be explained by one basic mechanism, their form shows considerable variation

and any one bar is modified by changing flow conditions as it grows. In other words, the variety of form is infinite, but a basic distinction between two general types can be made; those which are symmetrical (transverse) in shape with respect to the channel and those which are asymmetrical (diagonal). Cant and Walker (1978) also chose to distinguish symmetrical and asymmetrical bars.

The symmetrical bars are, not surprisingly given the complexities of the channel pattern, comparatively rare. They occur wherever there are fairly long straight reaches and are most common in portions of the main channel which extend diagonally across the flume. In this case their length may be as great as 1 meter (about 4 channel widths). These bars narrow downstream so that while aggradation takes place across most of the channel, non-aggradational troughs occur on either side of the bar. The whole of the downstream margin consists of an avalanche face. The bar surface becomes the channel bed and carries almost the entire sediment load. Commonly as the bar extends downstream, the upper portion develops a well-defined active channel along its axis while the flanks show less active sediment transport (Fig. 4.5). Cant and Walker (1978) described similar features in the South Saskatchewan River. These extended diagonally across the river and were termed diagonal bars.

Asymmetric bar development is much more common. This is largely because straight channel segments are rare and within a bend sediment transport and erosive capacity will not be uniform across the channel. Thus asymmetric bars closely resembling the alternating bars described earlier often occur immediately downstream of any scour hole positioned away from the centre of the channel. The foreset face which

Figure 4.5 Symmetrical bar. Note incipient division at its downstream end.


partially
inactive area

is present in the thicker bars faces across the channel and flow is diverted towards the opposite bank where the resulting circulation may produce another scour hole and bar facing in the opposite direction to the first (Figs. 4.6 and 4.7). At times, where interference from tributary channels is absent, a series of these formed at regular intervals and their modification occurred in the same manner as the original braided pattern. The less well-defined bars, only a few grains in thickness, do not always exert a strong influence on the flow and are often obliterated by a change in flow conditions before they can develop further.

4.3.2 Development of bars

These bars can therefore be regarded as dynamic bedforms whose ultimate origin (*i.e.* conditions for their existence) may be explained through theoretical analysis of the flow but whose formation and maintenance under natural conditions can be better related to specific local changes in flow *e.g.* expansion. Any local reduction in velocity will inevitably produce a decrease in sediment transport capacity and hence deposition. It is possible to identify several situations in which this might occur:

1) Downstream of scour holes,

a. involving the junction of two or more channels in which the channel downstream bisects the angle of incidence (see p 86). The reduction in sediment transport capacity as the flow leaves the scour hole produces a symmetrical bar.

b. in bends or resulting from confinement of flow by a bar upstream. Again, sediment transport capacity

Figure 4.6 Alternating asymmetric bars and scour pools.

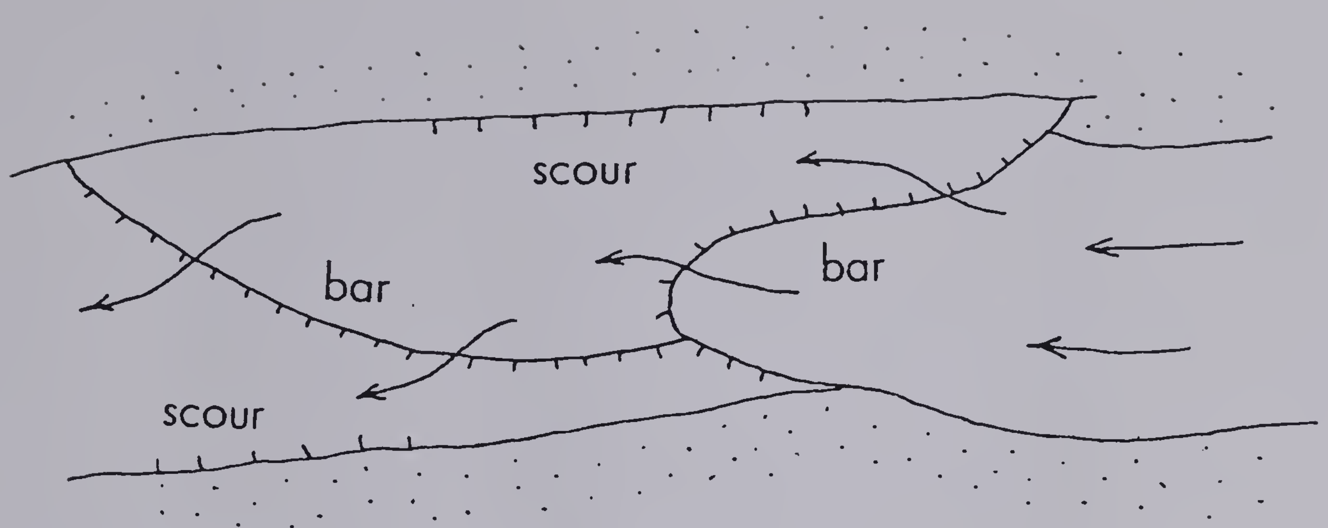

scour
bar
bar
scour

Figure 4.7 Asymmetric bar in Sunwapta River, Alberta.

declines downstream and deposition of an asymmetric bar results.

2) Downstream of flow expansion,

a. where a steep or confined channel segment emerges into a less confined reach.

b. where the flow in a scour hole is waning in strength and one channel begins to dominate and build a bar into the pool, reduction in capacity is a result of an abrupt increase in depth.

3) Where flow is overtopping banks and beginning to form a new channel. In this case the reduction in velocity and depth produces deposition on the overbank surface initially in the form of a shallow sheet or lobe which is enlarged as more of the flow is directed into the area (Fig. 4.8 and 4.9).

It is common for bars to show a second shallower lobe which may consist of coarser or finer material than the original over which it advances.

Occasionally it is possible to identify discontinuities in the bed which appear to be incipient bars but which usually disappear after only a few minutes. They are usually associated with a water-surface wave pattern consisting of two sets of diagonal waves intersecting at about 90°. The bedforms follow this pattern and consist of steps 1 or 2 grains high oblique to the channel. Occasionally two such steps form a V pointing upstream. Einstein and Shen (1964) and Chang *et al.*, (1971) both mention this kind of bedform. Guy *et al.*, (1966) show a network of such forms on the bed of an 8 foot wide flume at shallow depths. Chang *et al.*, (1971) proposed that there was a jump

Figure 4.8 Overflow bar. Produced by secondary circulation in bend and overtopping of banks.

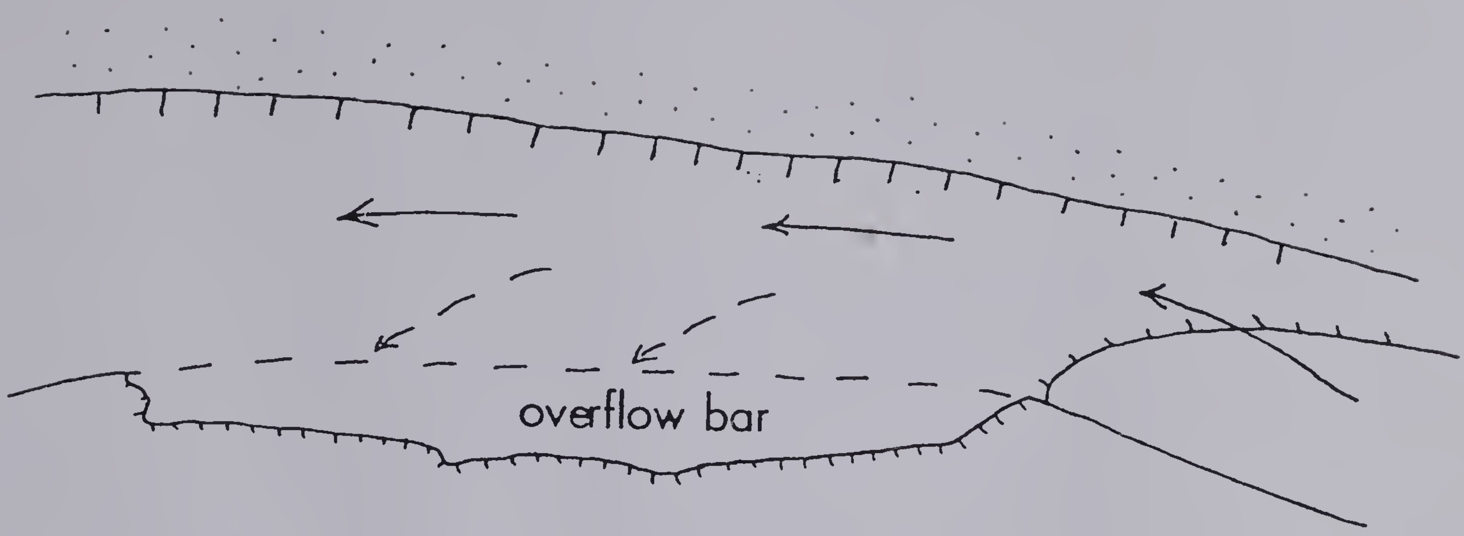

overflow bar

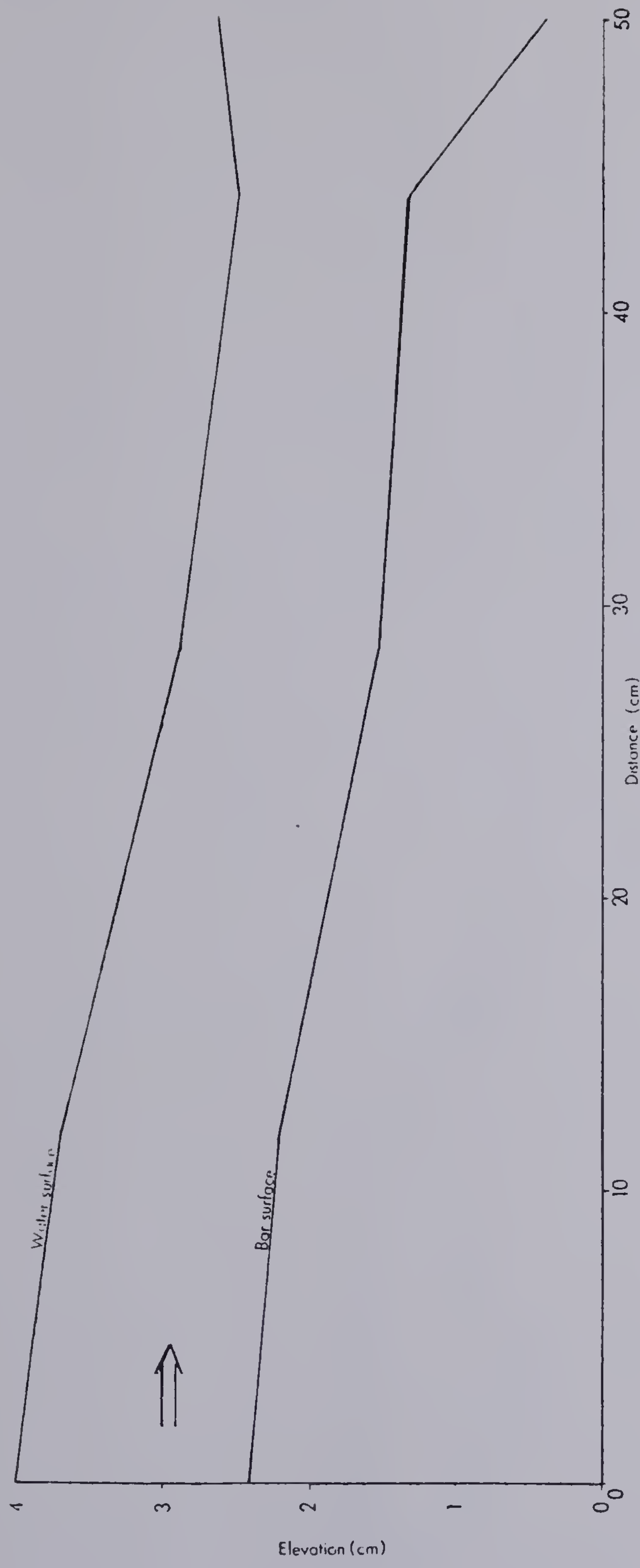
Figure 4.9 Overflow bar in Sunwapta River, Alberta.

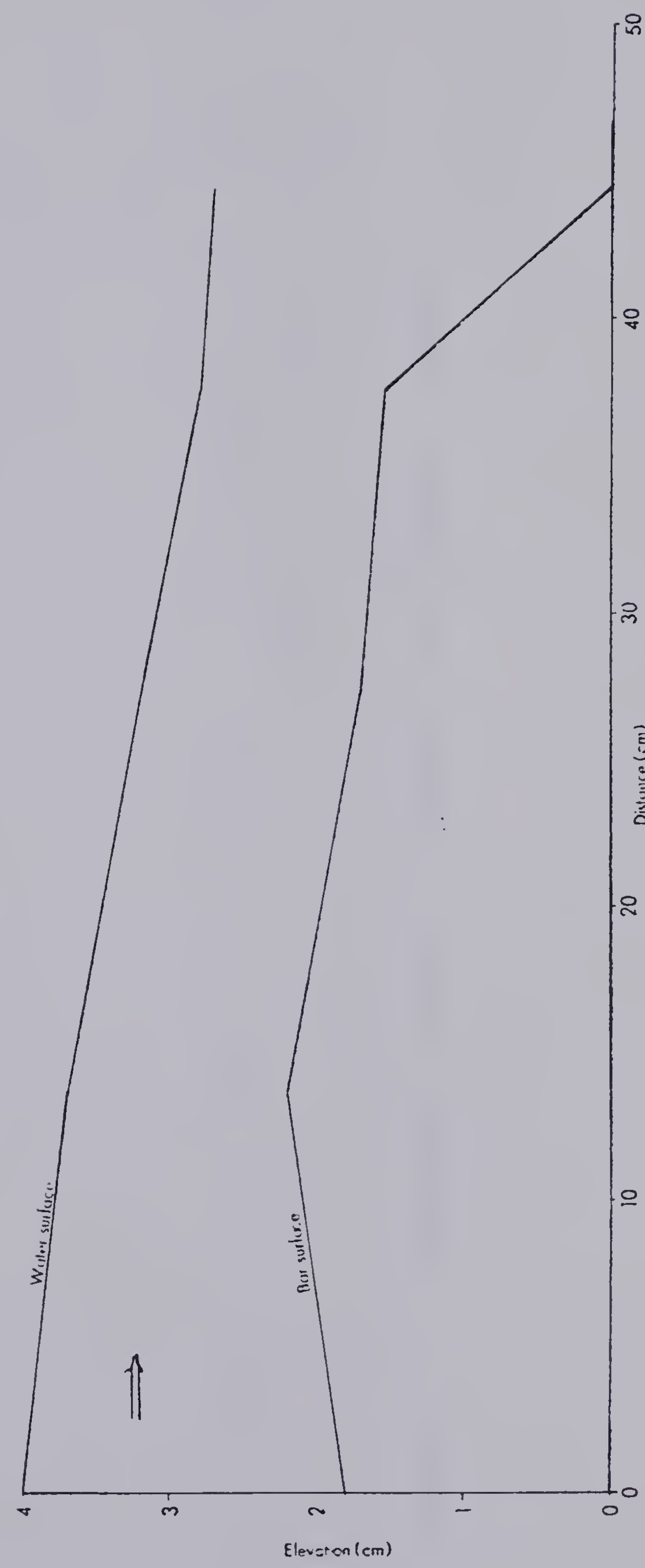
from supercritical to subcritical flow across this boundary and therefore a sharp change in sediment transport characteristics. Einstein and Shen (1964) indicated that such patterns are distinct from the alternating bar pattern and that the mechanisms involved are probably rather different.

It may be readily appreciated that deposition of sediment within a channel will cause some form of adjustment within that channel so as to accommodate the imposed discharge. The deposition of bars tends to reduce depth and bed slope and, in some instances, water surface slope. A typical profile of a bar might therefore resemble Fig. 4.10 and we can envisage a series of such bars producing a stepped profile analogous to a pool and riffle sequence of a meandering channel (Fig. 4.11). Some of the bar profiles surveyed show a measurable elevation (1-1.5 mm) of the water surface immediately downstream of the avalanche face of the bar because of the sudden transition from shallow to deep flow under subcritical flow conditions. The steepening of the water surface over the toe of the bar indicates a draw-down of water over this area and hence dissection of the end of the bar on a falling stage (Church, 1972). It is the adjustments which the channels make to the deposition of bars which lead to the abandonment of channels, exposure of bars and hence formation of the braided pattern.

Before considering the range of adjustments, and hence the construction of the braided deposits, it is necessary to consider another element of the braided river system which is important to the understanding of the river processes.

Figure 4.10 Longitudinal profiles of simple bar lobes.


Bar surface
Distance (cm)
Elevation (cm)
0
10
20
30
40
50
1
2
3
4


Water surface
Distance (cm)
Elevation (cm)
0
10
20
30
40
50
1
2
3
4

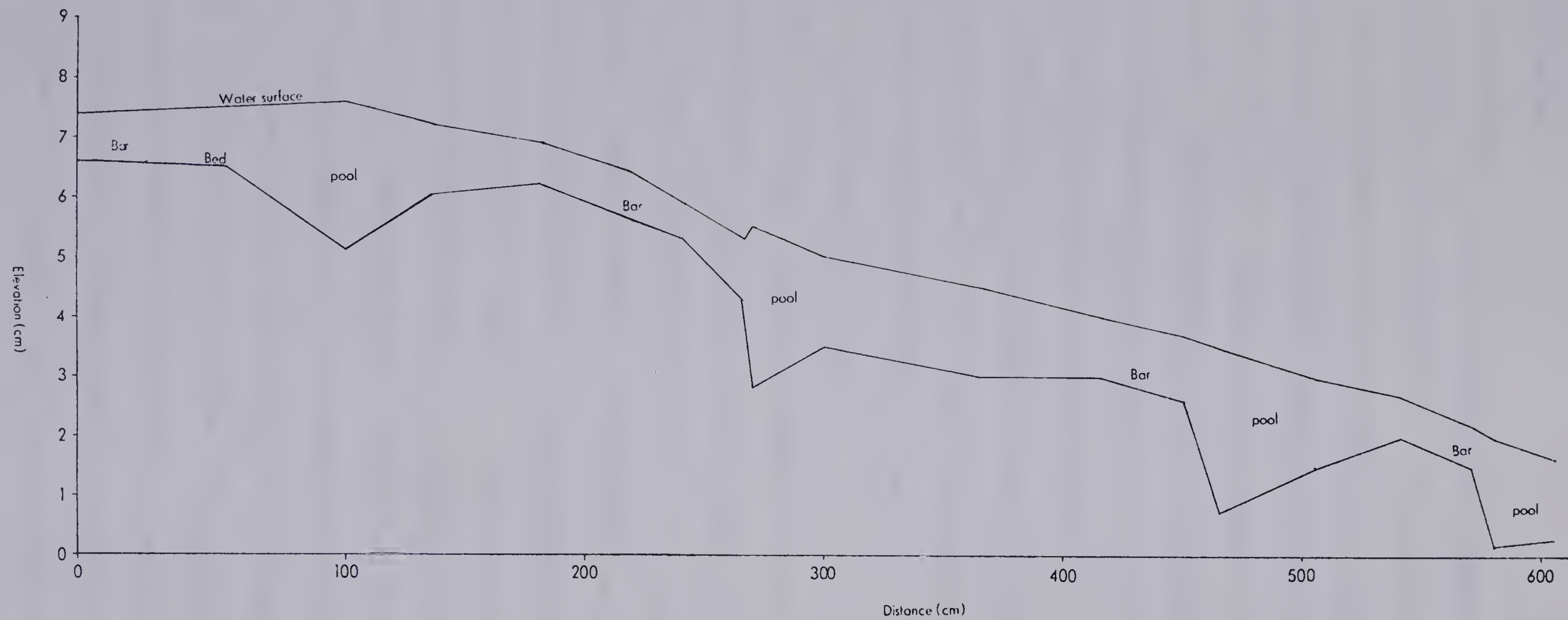


Figure 4.11 Longitudinal profile of bar/pool (riffle/pool) sequence

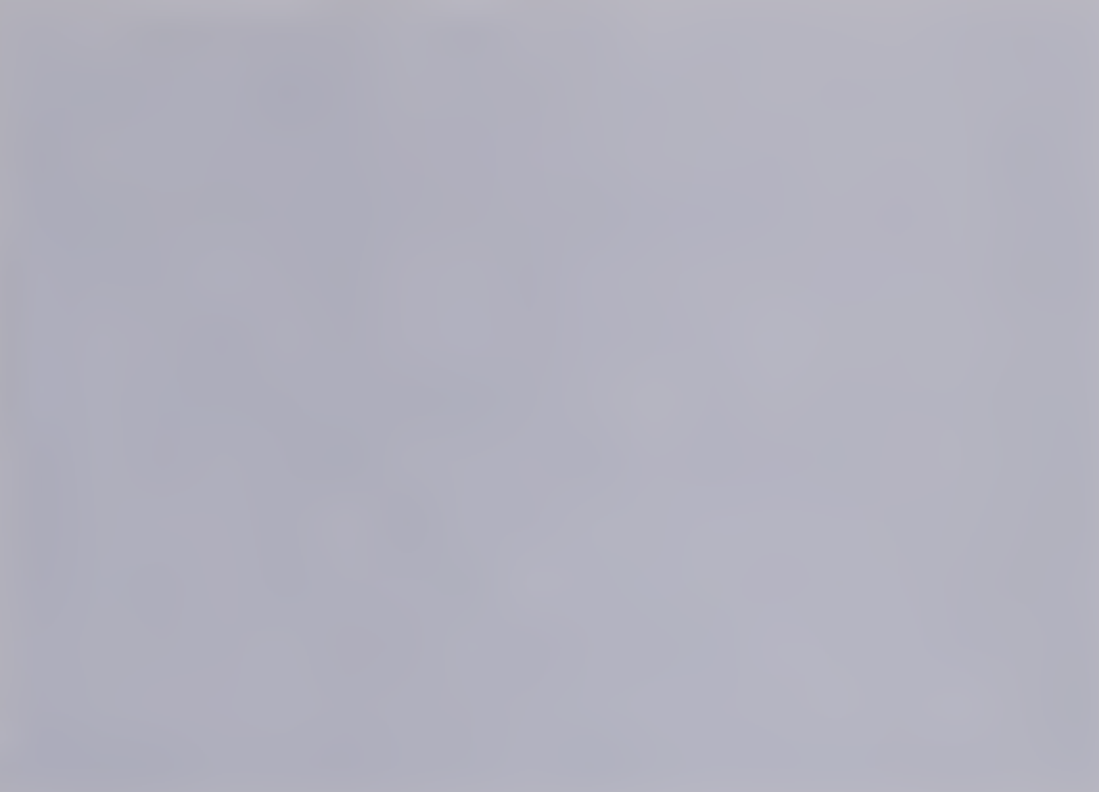
4.3.3 Scour holes

As indicated already, secondary flow elements producing local scour are important in bar construction. Information on scour holes in braided rivers is generally lacking although their existence, approximate dimensions and possible significance have been commented upon several times (see p 16). Laboratory experiments by Mosley (1976), under controlled conditions provided useful information on the variables controlling the dimensions of scour holes but those observed in the flume channel were generally of a more complex form.

In essence we can consider three basic types of scour; channel junction scour, scour associated with asymmetric bars, and scour produced by sheet flow over abandoned surfaces.

4.3.3.1 *Channel confluence scour.*

This is the type analysed by Mosley (1976) and the several good examples developed in the flume possess many of the characteristics he describes. Figure 4.12 shows photographs of a typical channel confluence scour. Depth of scour is often as much as five times the depth of the contributing channels. A cross-section of the deepest part of such a scour shows an elevation (1-2 mm) of the water surface and an approximately symmetrical form with concave walls and a width/depth ratio of 2 or 3. The long profile shows a steep headwall and a gentler upward slope downstream of the centre of the scour. Commonly small submerged levees form on either side of the channel immediately downstream of the centre of the scour hole. Observations show a movement of bed material diagonally outward from the centre of the scour hole on either side producing these levees as material is carried up the inward facing slope and avalanches down the outer face (see Fig. 4.13).



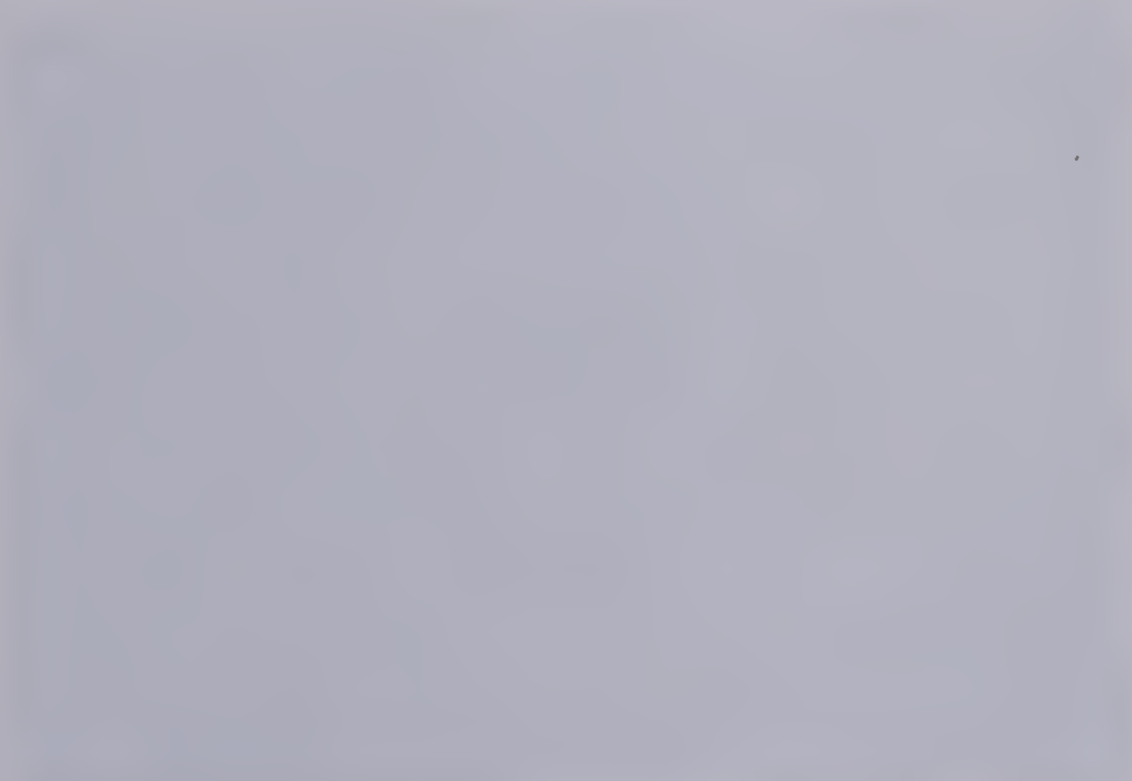


Figure 4.12 Vertical (a) and oblique (b) views of typical channel junction scour pool.

(a)

(b)

Injection of dye into the flow revealed a secondary flow identical to that described by Mosley (1976). The water from the two contributing channels converges at the upstream end of the pool and then plunges downward and outward along the bed, as it moves through the pool, producing two helical flow cells with opposite sense of rotation (see Fig. 4.13). When strongly developed there is comparatively little mixing of the water from the two channels but there is obvious turbulent eddy activity at the interface of the two cells. Maximum erosion occurs at the zone of flow attachment where the two downward currents impinge on the bed. Essentially this simple scour form resembles two meander bends back to back and shows the super-elevation of the water surface evident in meander bends.

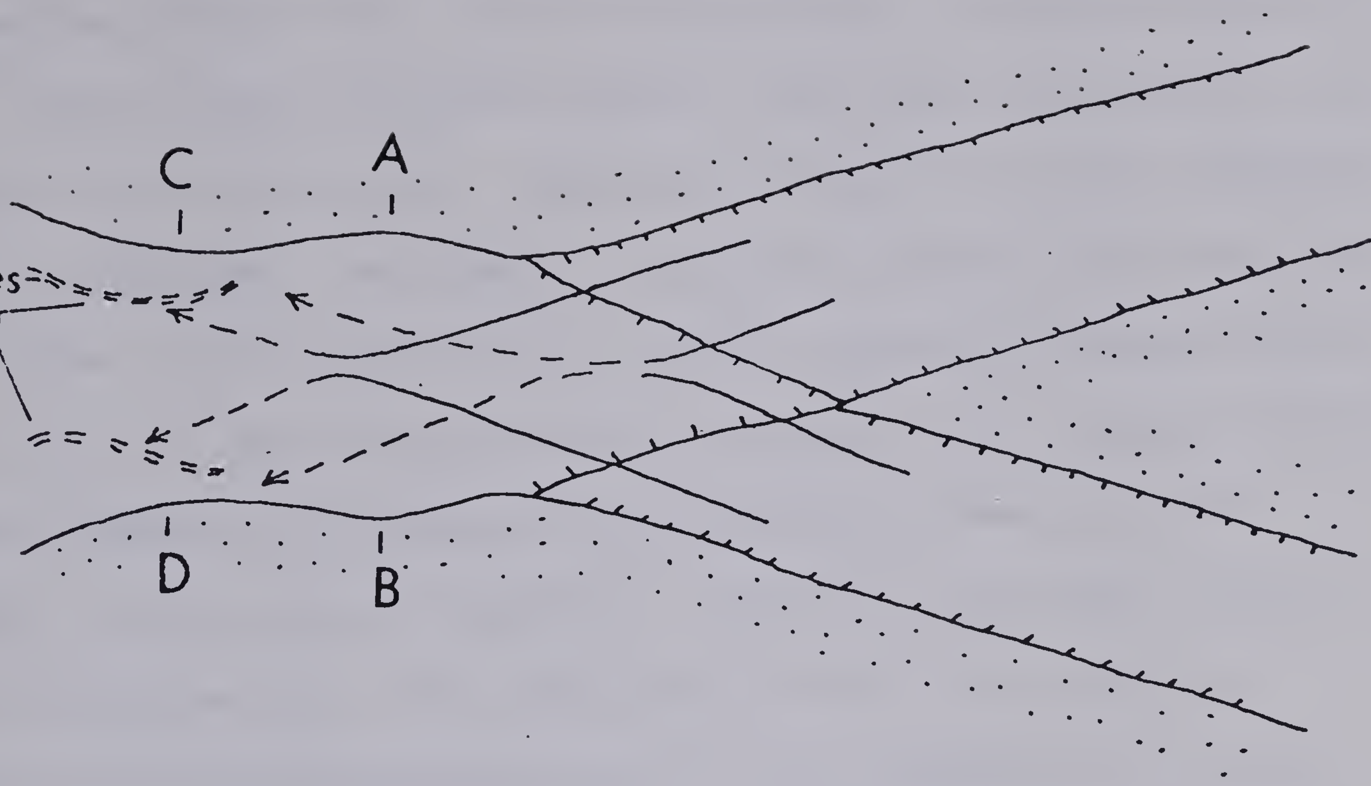
Treating the scour holes in the same way as meander bends, the strength of the secondary current (expressed as the ratio of the square of the velocity in the plane of the cross-section to the square of the main current velocity) has been shown to depend on three important variables. Briefly, these are a decrease in strength with increaseing depth/width ratio, increasing ratio of the radius of curvature of the bend to the channel width, and an increase in strength with increasing angle of deviation of the curve (Chow, 1959, p. 441). The super-elevation of the water surface relates to these variables in a similar fashion, increasing with velocity and decreasing with an increase in the radius of curvature/width ratio. In a controlled experiment Mosley (1976) determined that the two principal controls on the depth of scour in these junctions were the angle of incidence of the two channels (which is equivalent to the angle of deviation of the curve) and the proportion of the flow carried in each channel. A higher angle of incidence (up

Figure 4.13 a) Plan of channel junction scour showing flow paths and levees.

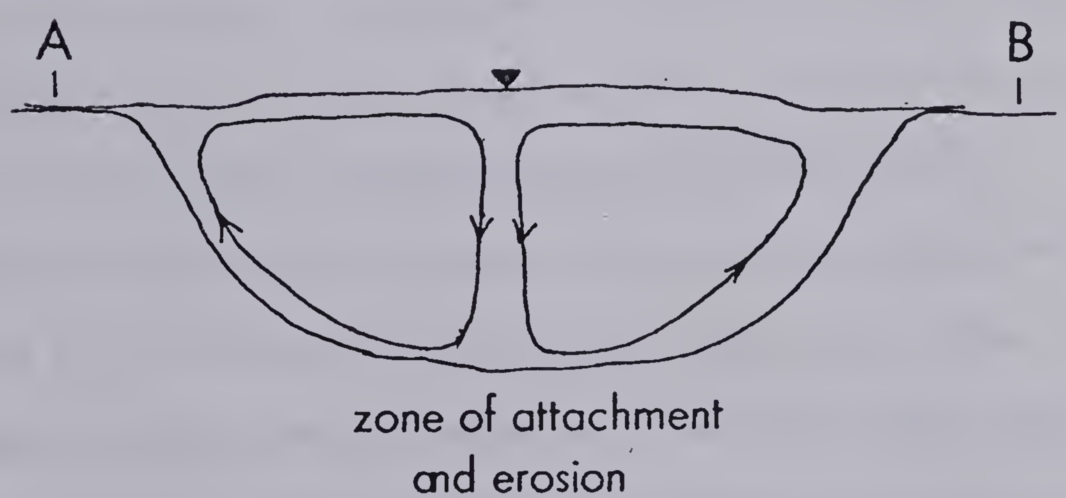
b) Flow structure in centre of pool.

c) Flow structure immediately downstream of pool.

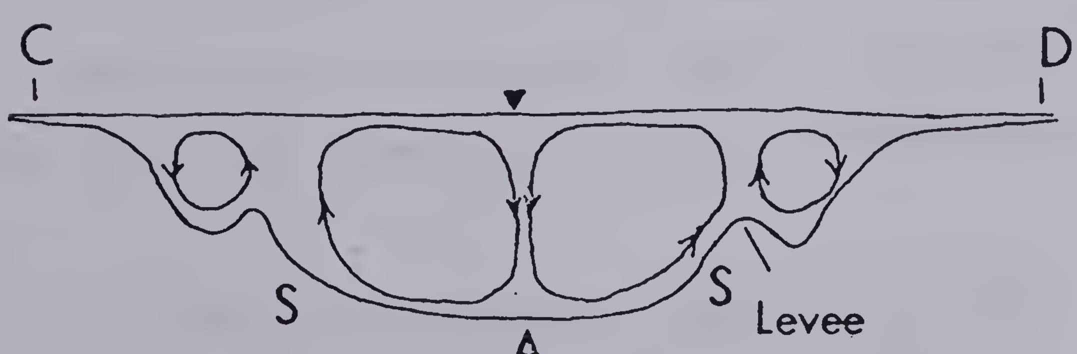
(a)



(b)



(c)



to a maximum of about 120°) gave a greater depth (everything else being equal) while a larger difference between the relative discharges of the channels gave a lower depth. One might also expect the total discharge to be of importance. An attempt to obtain the relevant measurements on scour holes in the flume model was largely unsuccessful because of the short period of time during which they remained stable. However, observations suggested that there was a relationships between the depth of scour and the angle of incidence. Figure 4.14 gives this relationship in graphical form. The relationship shows a large amount of scatter probably because differences in total discharge have not been taken into account. An attempt to allow for this by scaling scour depth with the depth of the contributing channels did little to improve the relationship. It should be pointeded out, however, that the range of angles involved covers exactly the range on Mosley's diagram over which the scatter is greater . No clear relationship exists between the relative discharges of the channels (expressed as the ratio of the larger to the smaller channel) and the scour depth but this may be due to the error involved in the discharge measurements using timed floats.

Provided conditions remain unchanged long enough we would expect there to be an equilibrium size for such scour holes. Once this has been reached erosion ceases and the scour holes simply become areas of sediment transfer redistributing material supplied from upstream. It is probable that bar formation downstream of the scour hole is originally supplied from the scour hole itself. Once established, the bar becomes an area for deposition of material eroded from further upstream.

In the simple case there is a tendency, given two channels of

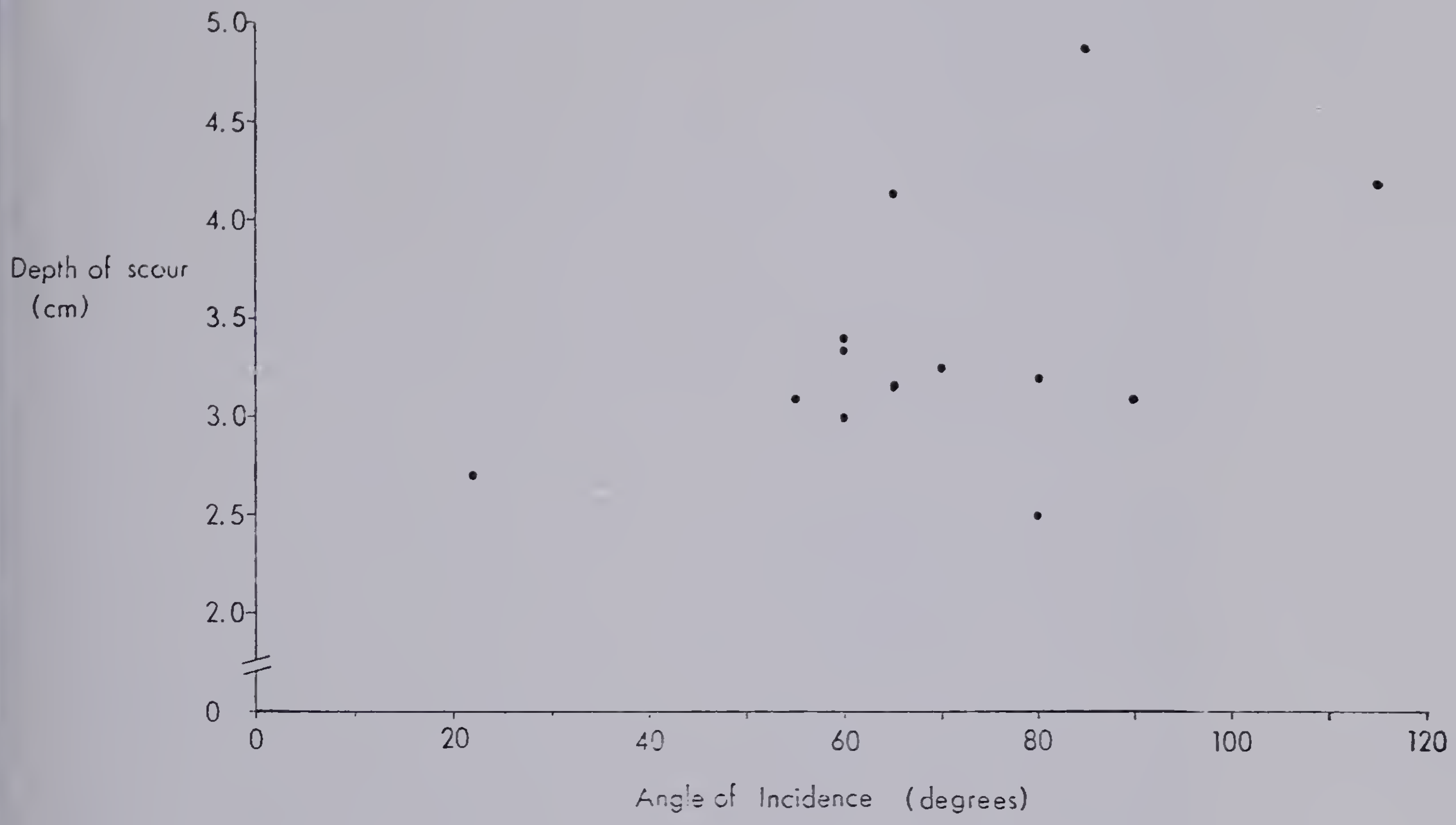


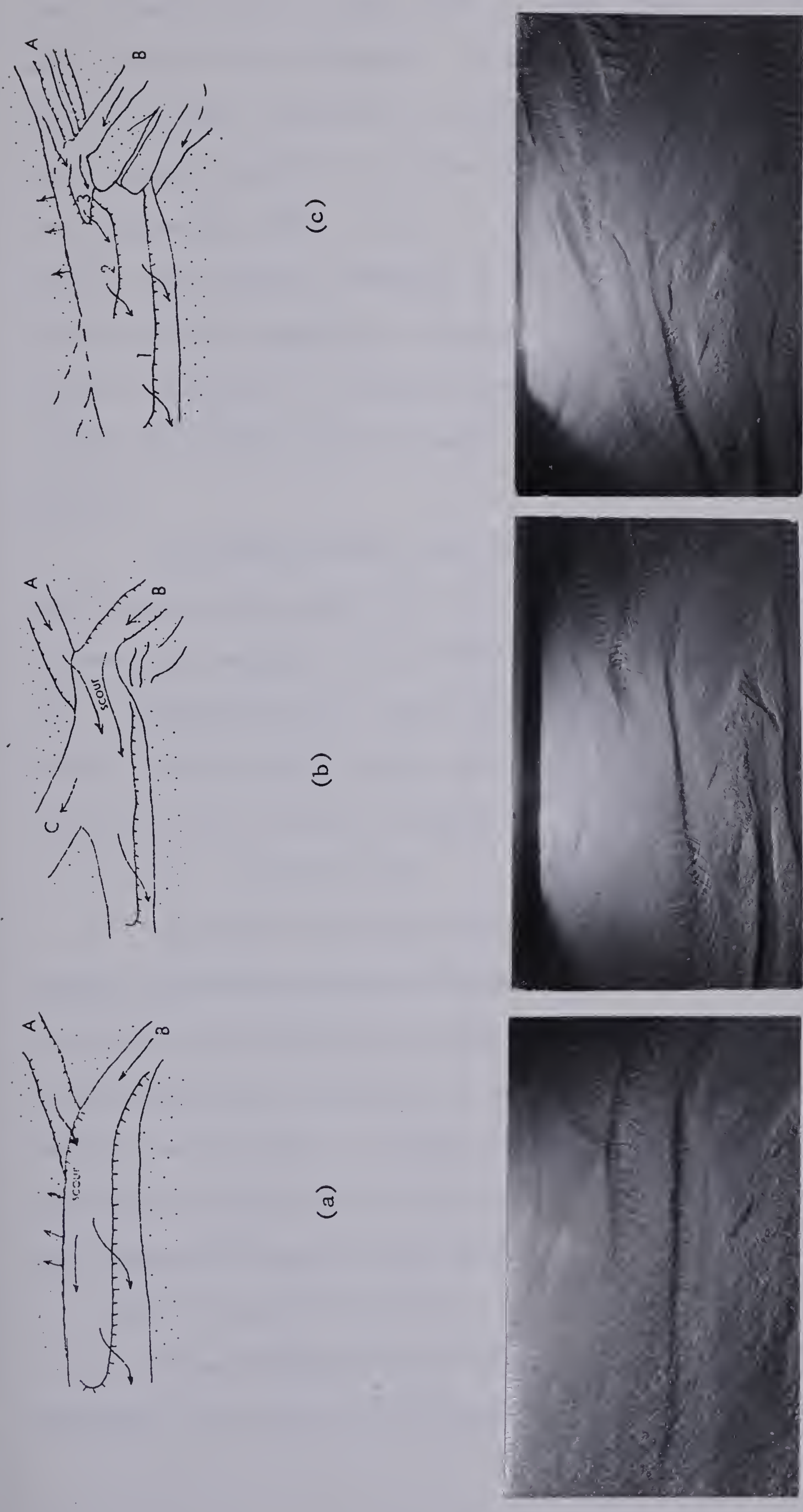
Figure 4.14 Depth of channel junction scour versus angle of incidence of contributing channels.

Figure 4.15 Migration of scour pool and associated bar construction.

(a) Scour hole produced by confluence of channels A and B builds asymmetric bar downstream because of dominance of B.

(b) A captures greater proportion of discharge and scour hole rotates in response. Aggradation and bank erosion downstream produce overtopping of banks at C.

(c) Discharge in both channels declines but B becomes dominant and lateral migration of the whole system builds bar complexes parallel to both B and C and produces a series of bars (1, 2 and 3) downstream as scour hole adjusts to changing flow conditions.


(a)
A
B
scour
(b)
A
B
C
scour
(c)
A
B
1
2
3

equal strength, for the scour hole to orient itself so as to bisect the angle between the two channels. In any other situation the orientation tends to parallel the stronger channel. This tendency for the scour pool to adjust rapidly to the prevailing flow conditions may result in some interesting events. Fig. 4.15 shows a scour pool responding to a change in the relative strengths of the incident channels by changing its orientation, migrating in response to an increase in the relative strength (discharge) of the left channel (facing downstream), and finally constructing new bars and a smaller pool as the total discharge declines.

Infilling of scour holes occurs in one of two ways. The first involves the construction of a delta-like bar across the pool as the secondary current loses strength because of a loss of contributing flow. Alternatively, scour pools may be obliterated by dissection of the headwall as one channel becomes dominant, secondary flow dies away and the channel moves toward the normal equilibrium profile.

4.3.3.2 *Asymmetric scour*

Any kind of secondary flow element in a channel will tend to produce differential sediment transport and local scour and fill. Thus many bends show small pools against their outside bank and the formation of asymmetric bars is necessarily associated with scour of a portion of the bed (see Fig. 4.6). Because such scour occurs only in one part of the channel, usually close to the bank, and because of its association with asymmetric bars, this type of pool can be referred to as asymmetric.

4.3.3.3 *Waning flow scour*

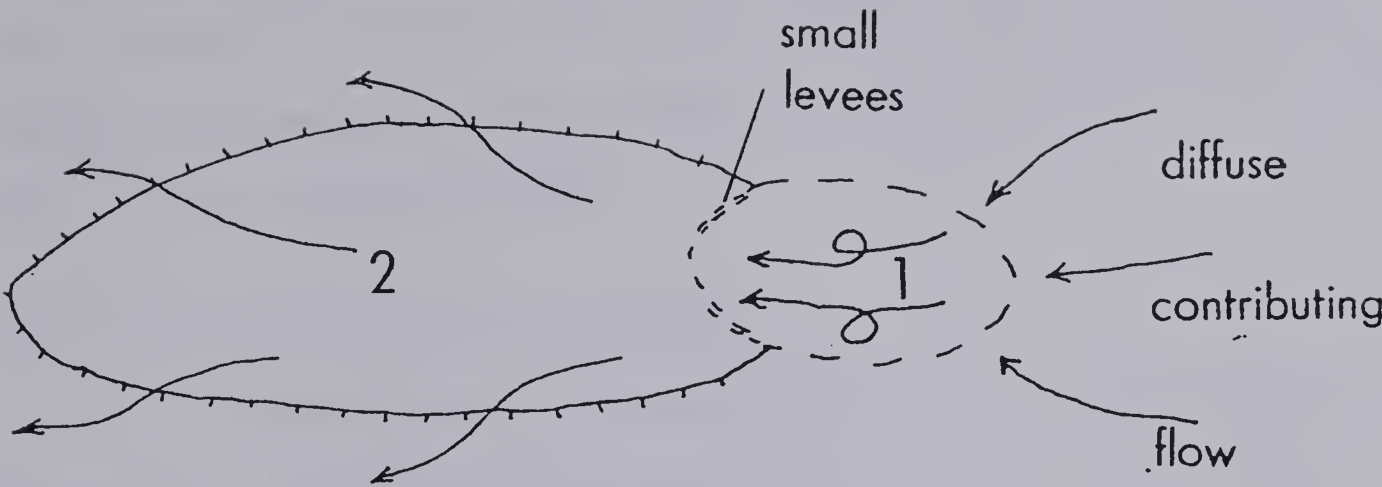
Observations on gravel braided outwash by Klimek (1972), Fahnestock and Bradley (1973) and Gustavson (1974) have indicated the

existence of comparatively small, almost hemispherical scour holes, often with small bars downstream found on the exposed surfaces of complex depositional flats. Explanations of such features usually involved boulders, melt out ice, or similar flow obstructions. Scour holes developed in the flume conform well with Gustavson's (1974) description in particular. They are almost circular in plan with a slight elongation at the downstream end. They have levees similar to those of channel junction scour deposited immediately downstream. Small bars of the material scoured out are deposited immediately downstream. Their formation is apparently associated with waning flow in areas recently abandoned. Small channels or troughs cause concentration of shallow sheet flow and at this convergence point turbulence is sufficient to erode these small pools (see Fig. 4.16). Because of their size the structure of the flow in these pools is difficult to see but they appear to be related to the channel junction scours although the contributing flow is of a more diffuse nature.

4.4 Modification of Bars and Construction of Braided River Deposits

The development of a model of longer term changes, through the identification of characteristic processes, is perhaps the area in which a model study holds the greatest advantage over field work. In particular, the reduction of the time scale is important in this respect. In fact, such description of the evolution of braided rivers is almost entirely lacking from published field studies. Often it is necessary to rely on description of bar forms to infer an evolutionary pattern (Bluck, 1974). Studies by Krigström (1962), Fahnestock (1963), Hein (1974)

Figure 4.16 Waning flow scour. Diffuse flow converges and produces turbulence and scour at 1 and deposition of small bar downstream (2).


small
levees
diffuse
contributing
flow
2
1

and Smith, N.D. (1974) provided information on short term (3 or 4 days) changes but so far only Cant and Walker (1978) have compiled anything approaching a comprehensive account of braided river processes over a longer period of time.

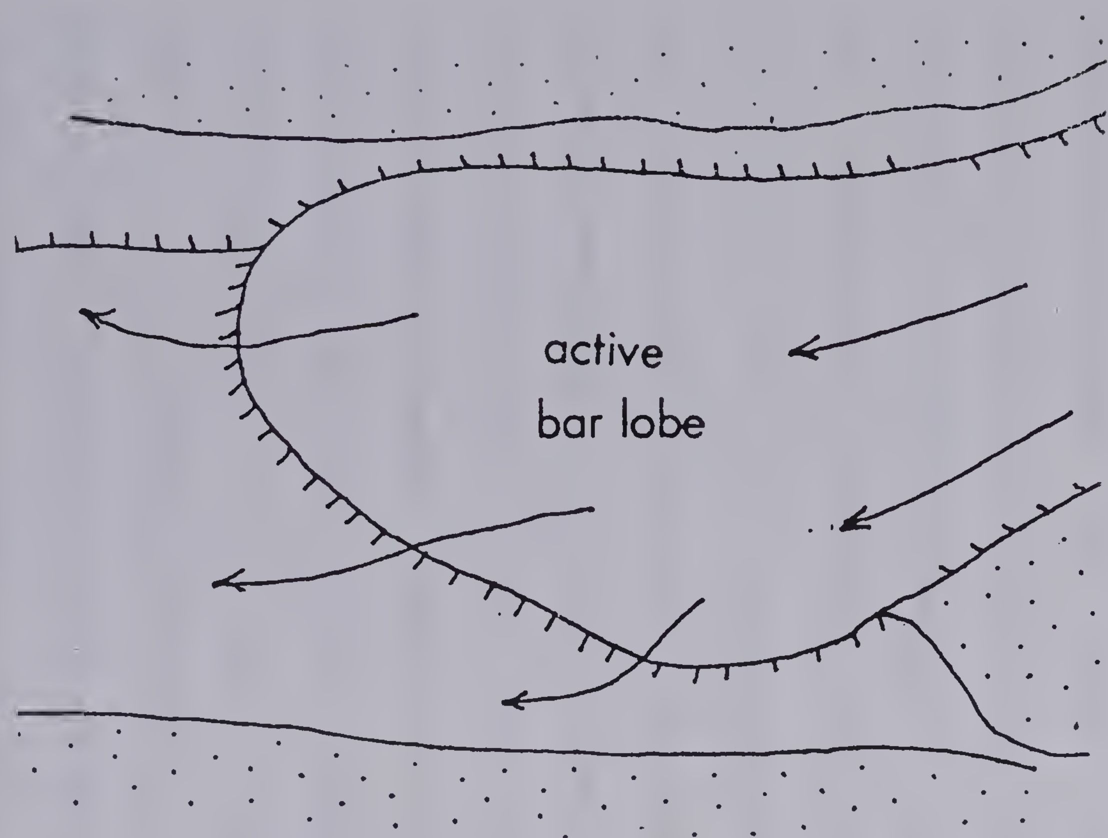
4.4.1 Adjustments to bar deposition

Following their original deposition individual bars may be subject to a number of modifications because they obstruct flow. There appear to be two basic adjustments to bar deposition, the first involves channel migration or division resulting in abandonment of a portion (usually the central section) of the bar. This process is described in more detail below. The second involves the incision of a single channel into the bar surface. It is common, as bar growth occurs for a section of the flow over the bar, usually a narrow central strip, to reach a flow condition close to critical and develop a pronounced train of standing waves and antidunes. This is apparently the result of the concentration of the flow in one part of the bar margin giving a greater sediment transport capacity in this area and hence headward erosion and incision. A narrow trough cut into the centre of the bar surface gradually widens and deepens, captures most of the flow and this results in the abandonment of the flanks of the original bar (see Fig. 4.17). Some published photographs (*e.g.* Klimek, 1972, Fot. 4) are suggestive of this kind of behaviour but only Church (1972) seems to recognize its occurrence. Church (1972) explained the process as the result of the channel attempting to return to equilibrium following the blocking of the channel by the formation of the bar. The shallow flow over the bar gradually loses sediment transport capacity and the restoration of deeper flow allows the sediment to be transferred through the reach.

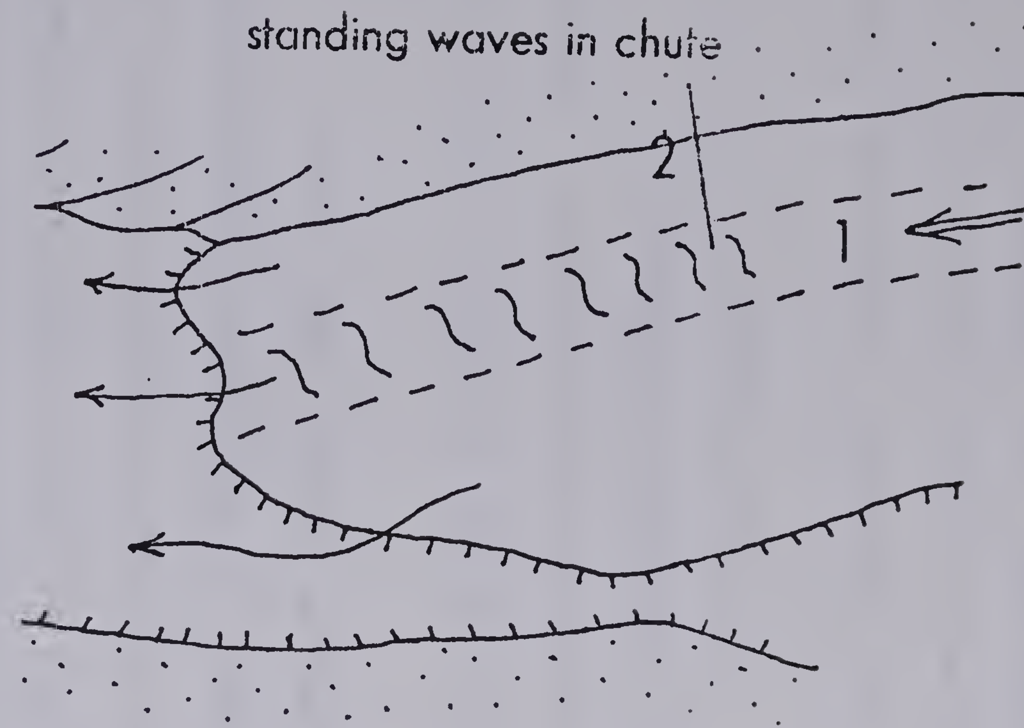
Figure 4.17 Incision on active bar surface.

(a) Large fully active bar lobe with shallow flow.

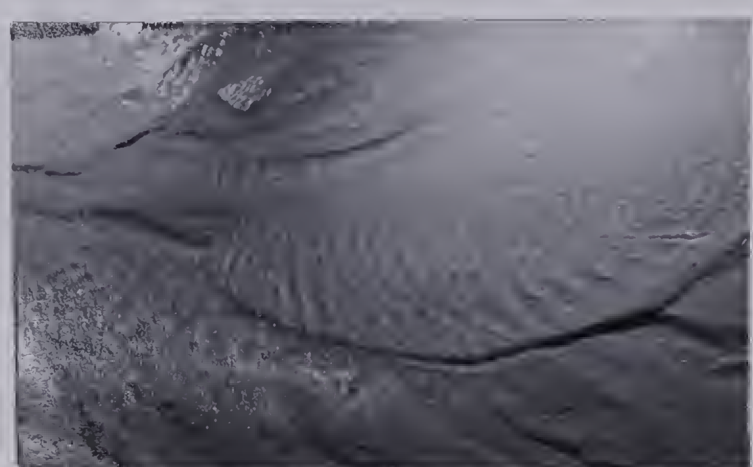
(b) As depth decreases scour chute (1) develops along bar axis lowering the water surface and leaving bar margins inactive and eventually exposed (2).



(a)



(b)



Hein (1974) and Smith, N.D. (1974) both recorded incision of bars in a similar way but in both instances a reduction in discharge producing draw-down of water over the bar margin was cited as the principal reason for incision.

4.4.2 Lateral migration and avulsion

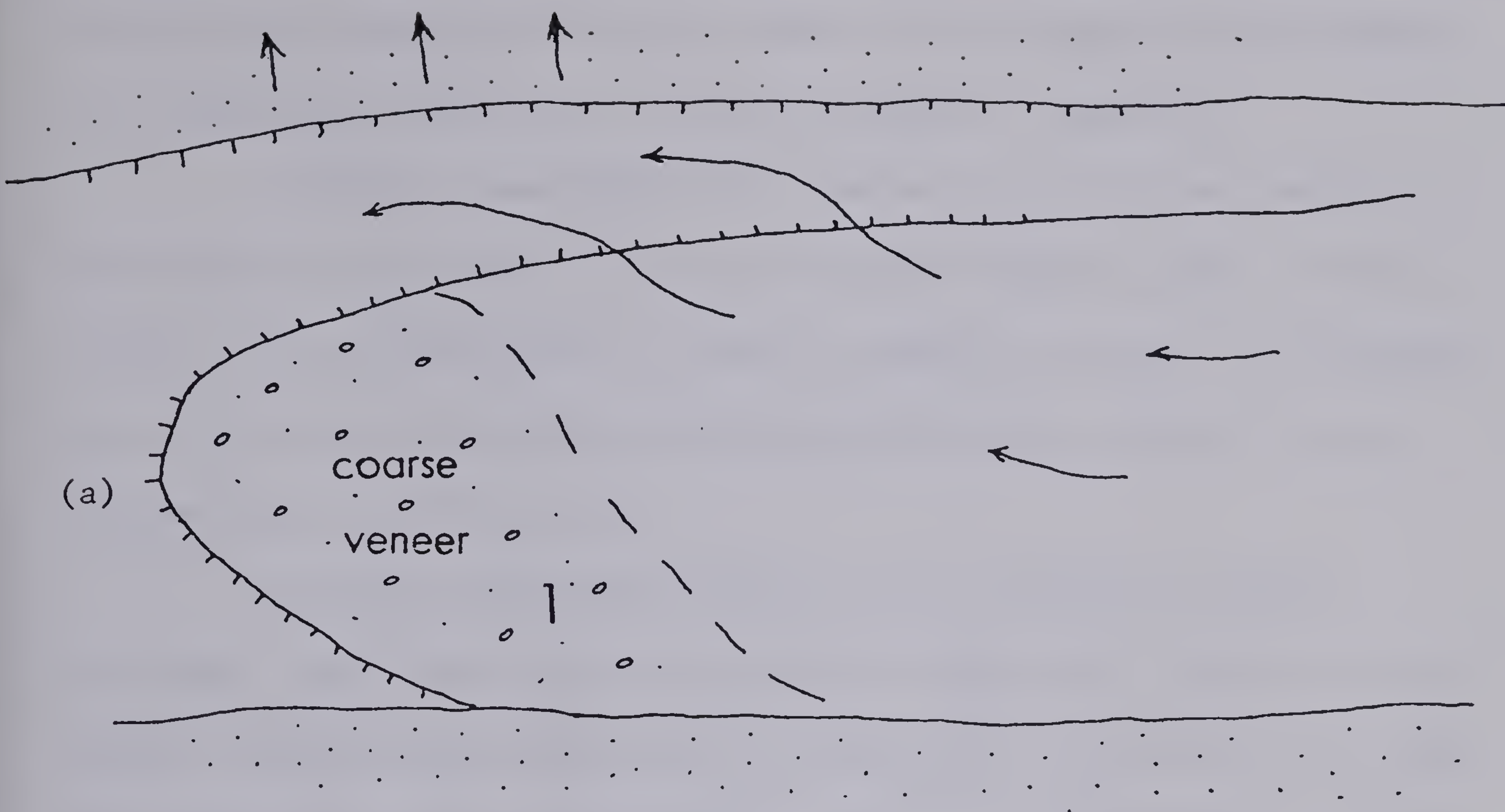
As indicated by Krigström (1962) lateral erosion is extremely important in braided rivers and the flume provides instances of several ways in which it may occur and of the kinds of deposits resulting from it.

In the model lateral erosion rates of 10-15 cm per hour were recorded, which is equivalent to a rate of 1-2 m per hour in a full-size river (assuming a model scale of the order of 100). Migration of channels occurs under a number of circumstances usually associated with bends and asymmetric bars or channel junctions and produces some distinctive bar forms. Fig. 4.18(a) illustrates how modifications following asymmetric bar construction may produce channel migration and construction of a distinctive type of deposit. The deflection of the main current by the bar leads to scour against the opposite bank and erosion of the bank. The downstream extremity of the bar tends to have the shallowest flow and as the channel widens this area is gradually abandoned. At low flow these bars are modified by dissection of the avalanche face and Fig. 4.18(b) shows an example from the Sunwapta River, Alberta. Immediately downstream of the bar the secondary currents in the scour pool move material back towards the inside of the bend and deposits them either as another asymmetric bar or in the form of gently dipping sheets two or three grains thick with stepped fronts facing the inside of the bend. If this type of process is repeated a deposit consisting of a series of abandoned

Figure 4.18 (a) Asymmetric bar deflects flow towards opposite bank causing bank retreat, channel migration and ultimately abandonment of the downstream end of the bar.

(b) Dissected asymmetric bar, Sunwapta River, Alberta.

(a)



(b)

lobes and overlapping sheets may be constructed (see Figs. 4.19,(a),(b)). Commonly the abandoned lobes are sites for the deposition of a veneer of coarser particles before becoming abandoned completely.

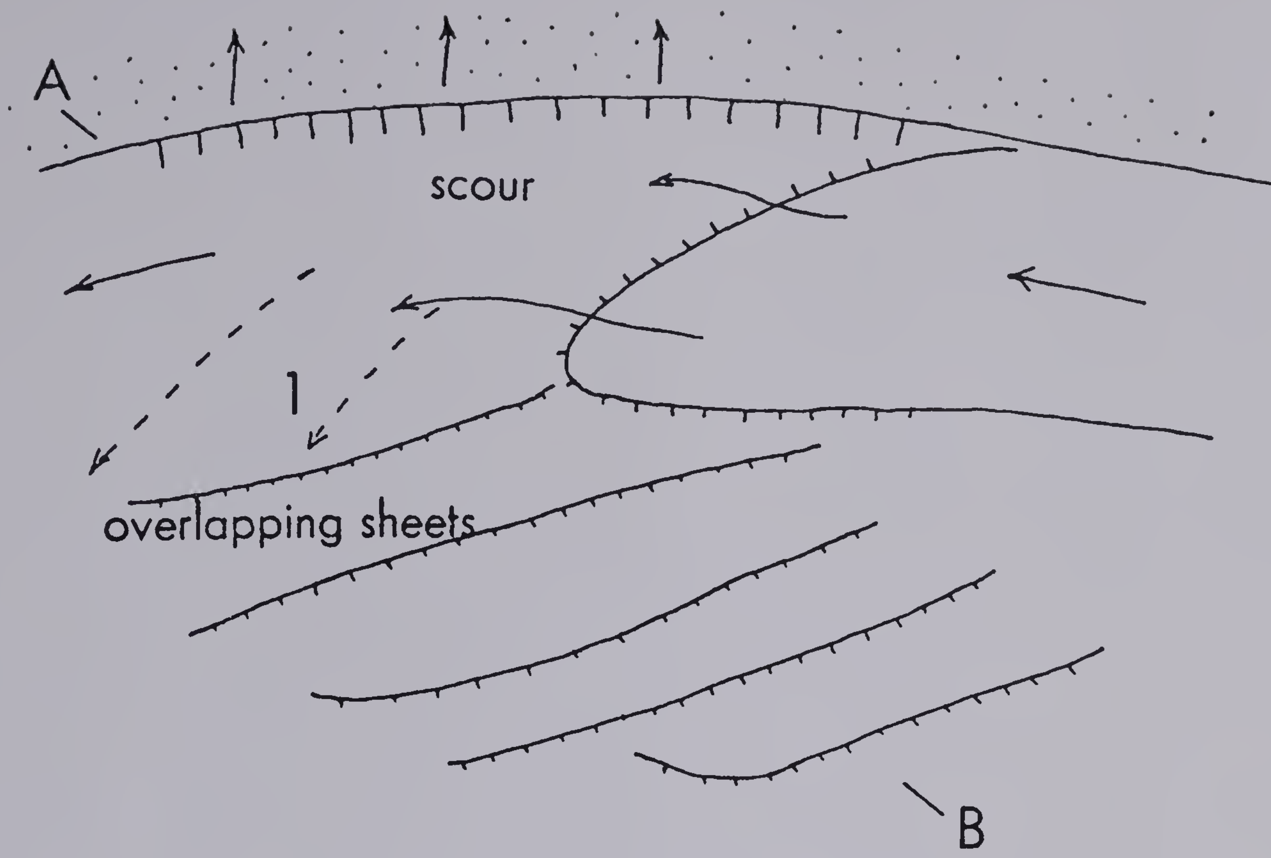
Migration associated with channel junction scour occurs as the relative discharges in the contributing channels change and may result in the construction of deposits, similar to those just described, with the overlapping sheets being represented by a series of superimposed bars (see Fig. 4.15).

Bar and channel migration may also combine to produce avulsion. Bank erosion and the raising of the water surface by deposition in the channel may result in overtopping of the banks under many circumstances but most commonly this occurs on the outside of a bend downstream of the apex in a manner similar to chute cut-offs in meandering channels.

4.4.3 Channel division

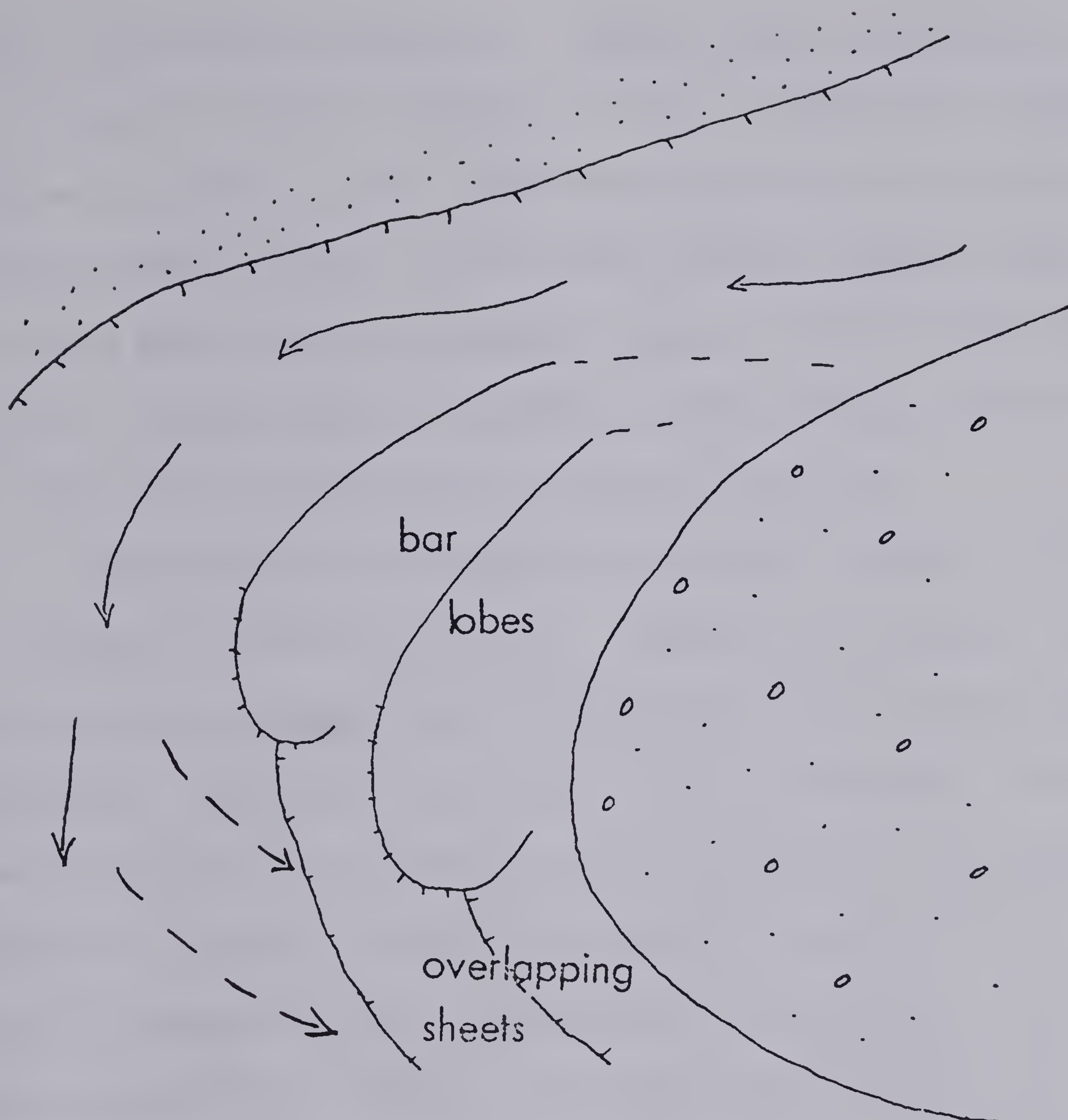
The deposition of bars may also result in channel division. The fundamental division process described by Leopold and Wolman (1957) was duplicated on occasions in the flume but usually only in the reach at the head of the flume. In other words, it was often the process by which initial division occurred but, downstream division associated with bar lobes was more prevalent. Note also that the initial pattern development involved bar lobes rather than the Leopold and Wolman (1957) process. The process has already been described and events in the flume followed Leopold and Wolman's (1957) description. One point which was not emphasized by Leopold and Wolman is that where the two channels rejoin downstream of the bar nucleus the low angle junction

Figure 4.19(a) Channel migration alongside asymmetric bar and construction of overlapping sheets.


A
scour
1
overlapping sheets
B


A
B

Figure 4.19(b) Abandoned lobes and overlapping sheets,
Sunwapta River, Alberta.

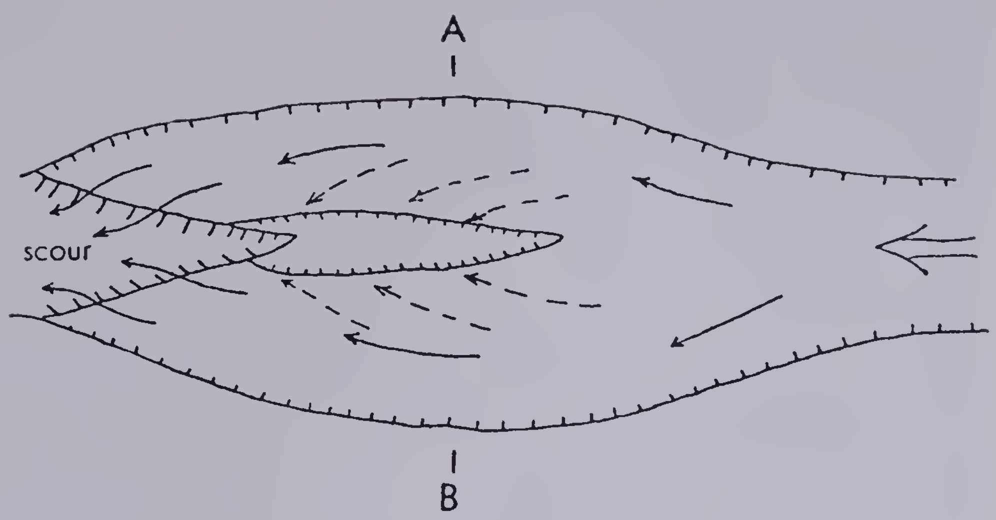

bar
lobes
overlapping
sheets

produces a long shallow scour hole. Although their illustrations (Fig. 35, p. 47) clearly show the presence of such a feature, they apparently attached no importance to it. Immediately upstream of the scour hole the weak secondary currents in the bends construct shallow sheets with their leading edges facing one another across a shallow trough (see Fig. 4.20). Channel migration may add to these original sheets in the manner illustrated in the section on lateral migration.

Construction of bar lobes may lead both directly and indirectly (by avulsion) to channel division. Generally, the centre of the downstream margin of symmetrical or asymmetrical bars is the highest and shallowest. Anything which causes a fall in the water surface or decrease in depth (*e.g.* increase in width, reduction of discharge) may then result in this portion of the bar becoming inactive first. It is here that the greater amount of deposition of bedload will occur to form the nucleus of the deposit. The flow will then split round this nucleus often resulting in the destruction of the avalanche face and the development of new bar lobes, usually with foresets oriented obliquely to the channel, facing away from the nucleus. This process has been described in some detail by Cant and Walker (1978). The inactive surface often accumulates a further veneer of sediment before becoming completely abandoned and exposed (figs. 4.21, 4.22). Notice that in fact this division on the bar surface is actually similar in principle to the Leopold and Wolman (1957) type.

These first two processes constitute primary anastomosis in Church's (1972) terminology. Secondary anastomosis involves the reoccupation of previously abandoned channels by water overflowing from active channels. Both lateral erosion and aggradation within the

Figure 4.20 Leopold and Wolman type channel division. Note sheet deposition on inside of bends and scour at channel junction.


A
scour
B

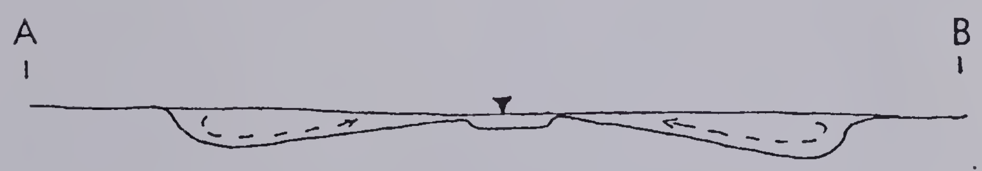

A
B

Figure 4.21 Flow division on bar surface.

(a) Well-developed bar shows flow diversion and scour on both sides.

(b) Scour and flow diversion produces erosion of banks and as the bar aggrades the centre of the downstream face becomes inactive.

(c) Flow division complete. Inactive area completely exposed and develops coarse veneer. New channels develop bars (1 & 2) and asymmetric scour (A and B) and begin to add further depositional units to the central exposed area (3).

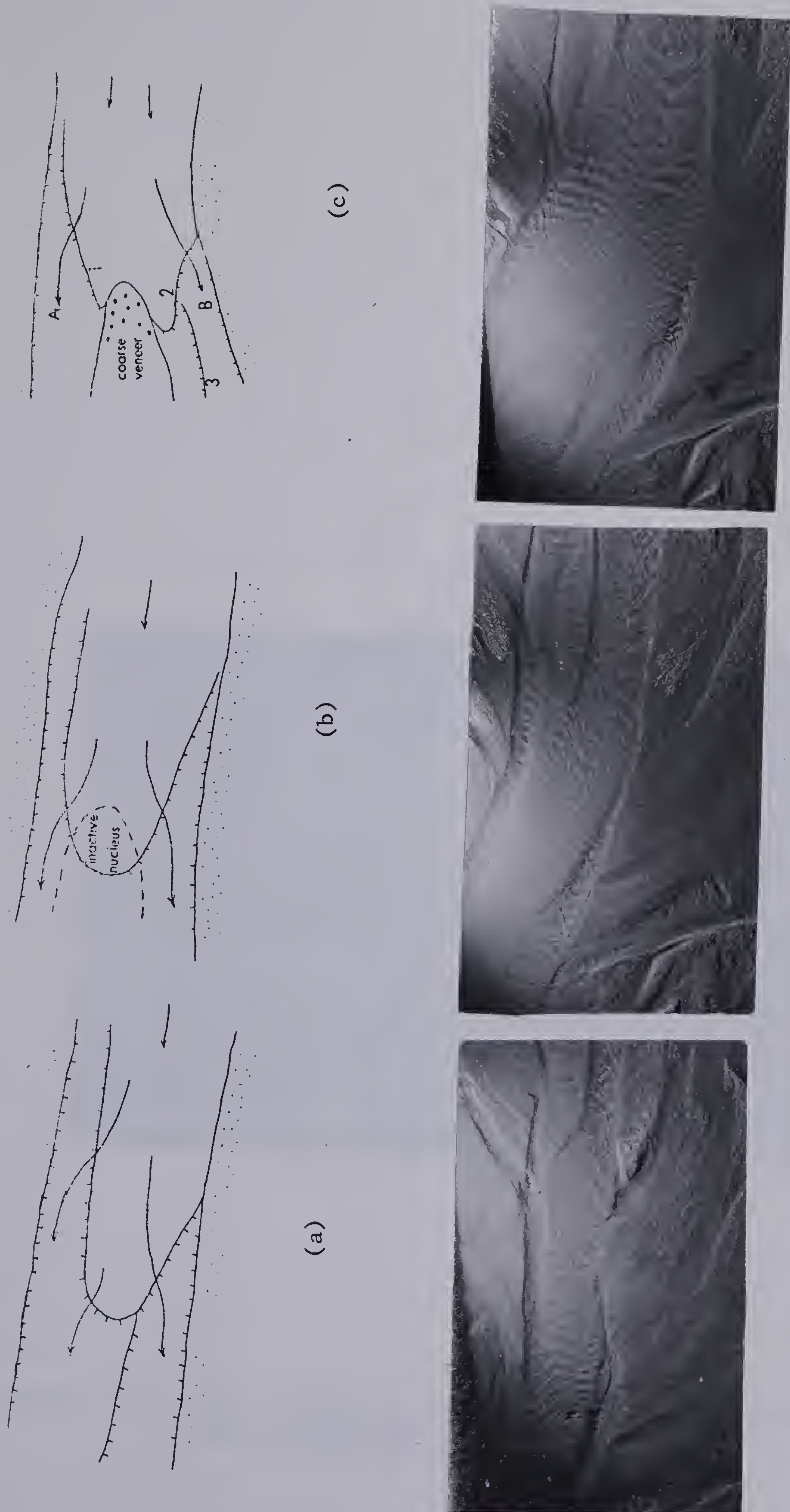

(c)
A
B
2
3
coarse veneer
(b)
inactive nucleus
(a)

Figure 4.22 Flow division on bar surface in Sunwapta River, Alberta. Flow is away from the camera.

channel contribute to this process. Avulsion usually begins with shallow sheet wash over the abandoned surface with concentration of flow into depressions on the surface. Usually an abandoned channel retains little of its original form, being filled in by minor bars, as flow declines. As flow increases over the surface part of the bedload may be carried out of the main channel and begin to build a shallow sheet across the old surface (Fig. 4.23). Commonly this stage is accompanied by headward erosion at the downstream end of the exposed surface as the flow begins to concentrate along a particular route. This ultimately results in the incision of the channel abandoning the initial sheet deposits at the head of the new channel.

When fully established, it may be difficult to determine how a particular flow division occurred, but one formed by primary anastomosis will tend to show an identifiably systematic structure to the exposed area between the channels while division by avulsion will lack this structure.

4.4.4 Construction of larger units

Having developed a description of a variety of erosional/depositional forms and processes we can now examine more complex units and identify the sequence of events leading to their present form. Clearly, slight variations in the processes operating produce an infinite variety of forms, but it is possible to illustrate the sort of sequence of events which may occur with reference to some well-defined bar complexes which exist. These resemble the medial and side bars of Bluck (1976).

Figure 4.24 shows a medial bar complex formed near the head of the flume. Observations of this complex in particular, and of other

Figure 4.23 Avulsion features. Aggradation in main channel allows overflow to left and as flow gains in strength bar (1) is built across the overbank area. Headward erosion scars (2) are common as renewed flow alters the channel profile.

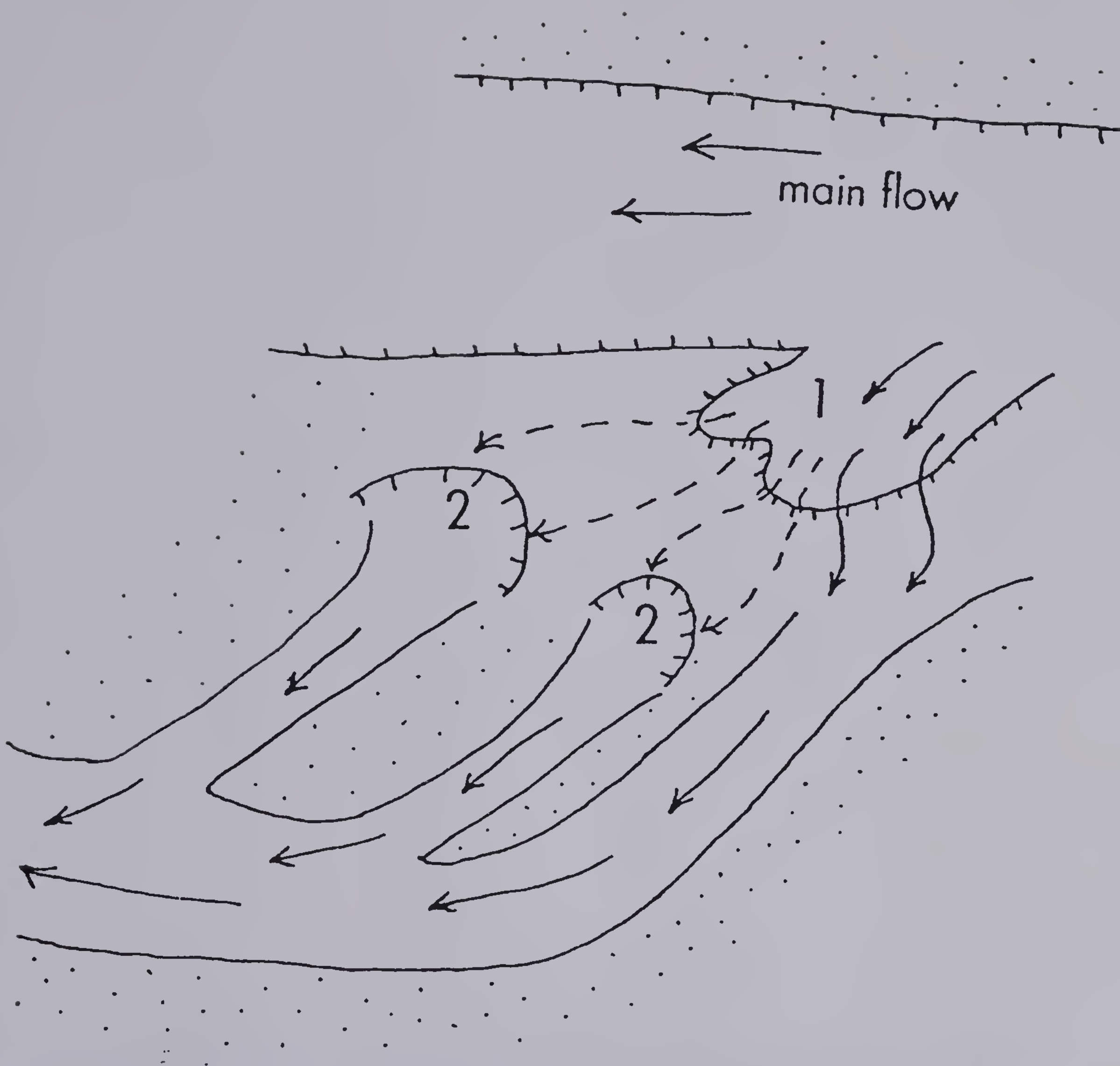
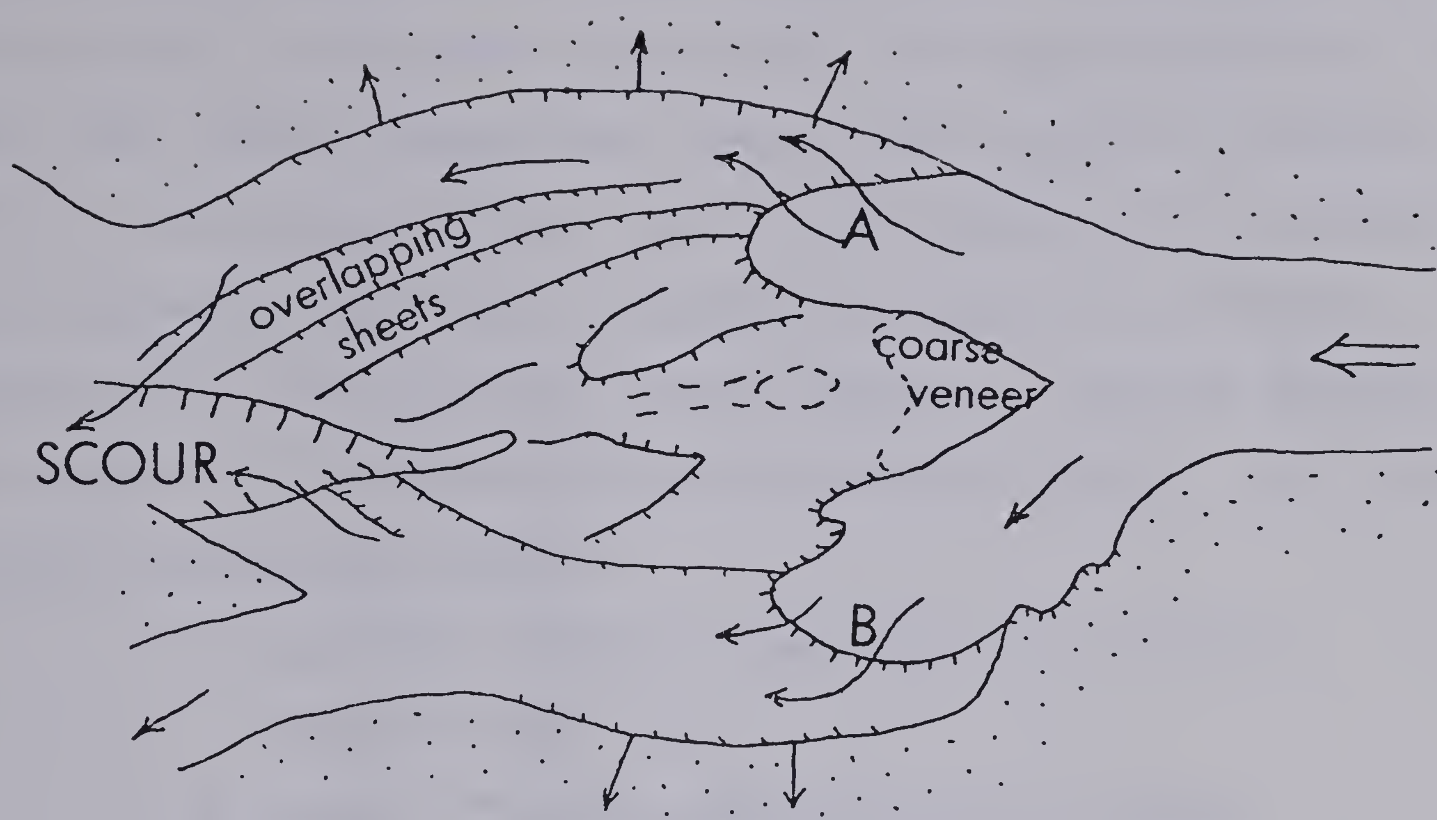

main flow
1
2
2

Figure 4.24 Medial bar complex. Structure shows:

a) Complex of convergent lobes, abandoned channels and small scour holes.

b) Present active bar lobes (A and B) producing further channel migration and sediment accretion.


overlapping
sheets
A
coarse
veneer
SCOUR
B

similar forms, suggests the following sequence of events leading to its construction. Initial flow division was of the Leopold and Wolman (1957) type but other similar complexes were initiated from division on transverse bars. Initially, then, we have a small exposed nucleus with two channels with asymmetric cross-sections rejoining downstream in an elongated scour trough. From this point lateral migration of the type described in section 4.4.2 is responsible for the complex formation. This leaves several identifiable features:

1) a partially infilled central trough often showing waning flow type scours.
2) evidence of slight upstream migration of channel bifurcation producing a secondary nucleus and coarse veneer upstream of the original one.
3) convergent elements consisting of former channels infilled by sheet deposits.
4) overlapping sheets produced by lateral migration, particularly in the downstream portion of the bar.
5) bar lobes of the present active channels.

The upstream half of the complex tends to show remnant bar lobes while the downstream portion is apparently dominated by overlapping sheets.

Migration of this kind involving only one channel would produce a lateral bar (point bar?) of similar construction (see Fig. 4.19(b). One other possible mechanism for the construction of these kinds of complexes is illustrated in Fig. 4.25. Development of an asymmetric bar in the upstream reach leads first to construction of a bar in channel A downstream but bank erosion caused by the upstream bar gradually diverts flow away from channel A leading to dissection of the

Figure 4.25 Channel migration process building either medial or point bar complex.

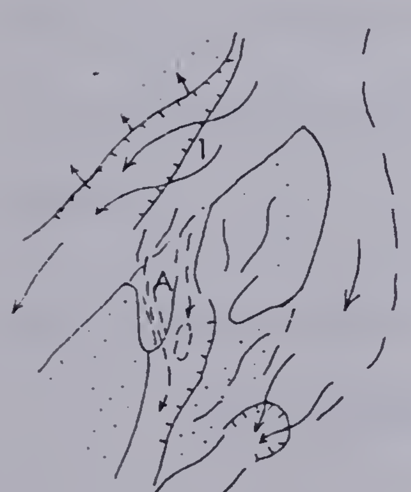
(a) Flow divides and establishes channel through A.

(b) Bar deposition in main channel (1) produces sinuous thalweg, secondary currents and bar deposition in A as well as scour and bank erosion at B.

(c) Extension of bar 1 diverts flow away from A and as flow declines dissection of bars and partial infilling of scour pool follows.

(a)

(b)



(c)

features formed at high flow and the partial infilling of the scour holes. Avulsion on the outside of a bend would have the same effect of depriving the former channel of flow.

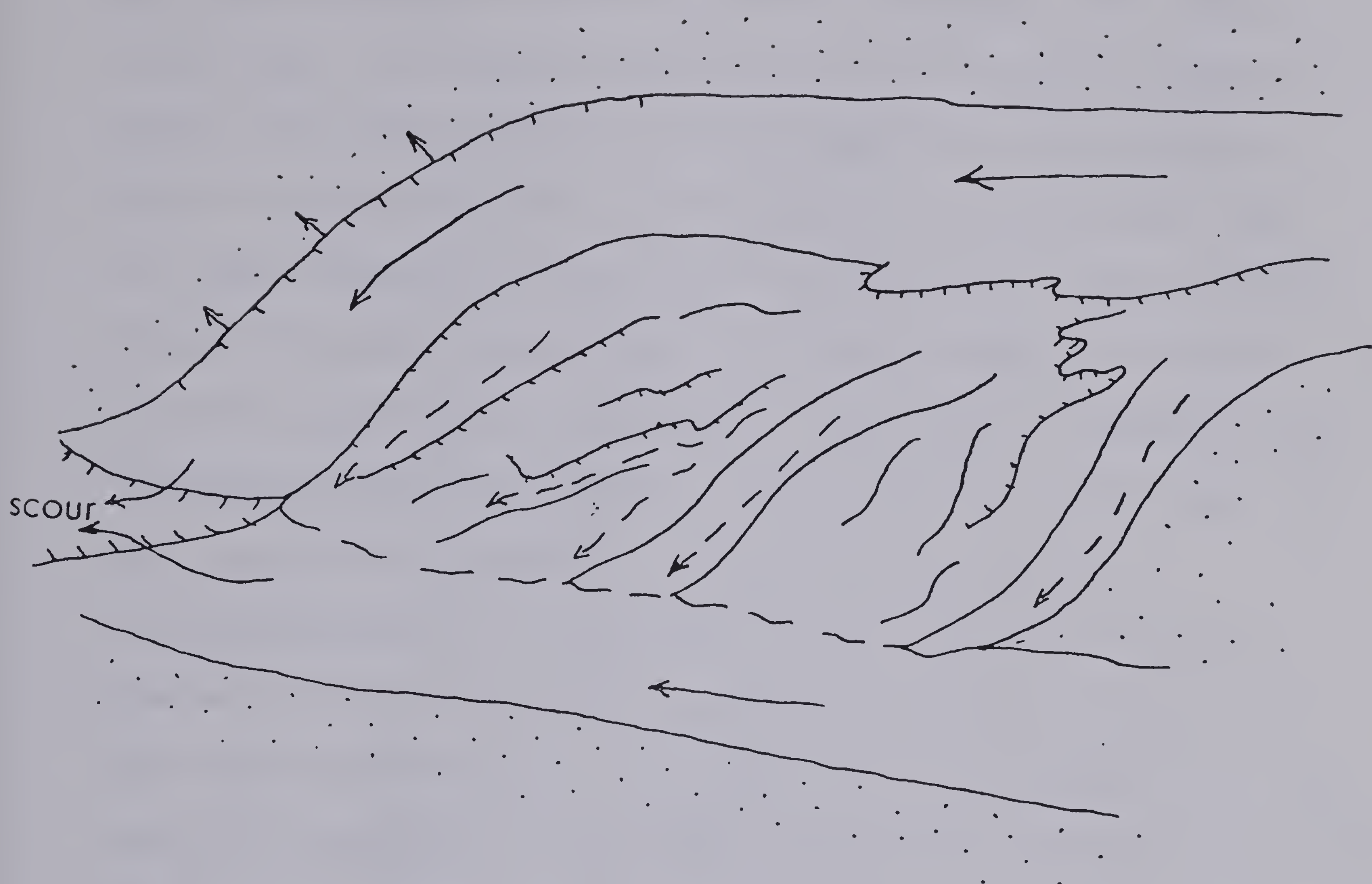
One further illustration (Fig. 4.26) shows a complex produced by the progressive downstream migration of a channel cutting diagonally across the flume. These closely resemble bar complexes illustrated by Krigström (1962) and Bluck (1974, 1976). The deposit consists of sheets and a series of bar lobes and, if the situation is stable, the area may be consistently reworked as periodic avulsion reoccupies different portions of the complex producing minor changes in its structure.

Exposure of any complex flat may be by incision of the main channel or sudden avulsion abandoning that portion of the river. Bar complexes of systematic construction *i.e.* deposited from a single ordered sequence of events, may be distinguished from those complexes developed by a series of different events by examining the structure of the deposits in relation to the adjacent channels. Clearly a bewildering variety of single bars and complexes exist in various stages of deposition or dissection but the descriptions above should serve as an illustration of the kinds of basic forms and processes involved and the way in which they may combine to construct braided river deposits.

4.4.5 A heirarchy of forms?

The dissection of complexes could be viewed as a larger scale

Figure 4.26 Diagonal complex. Produced by succession of bar migration and avulsion in main channel.

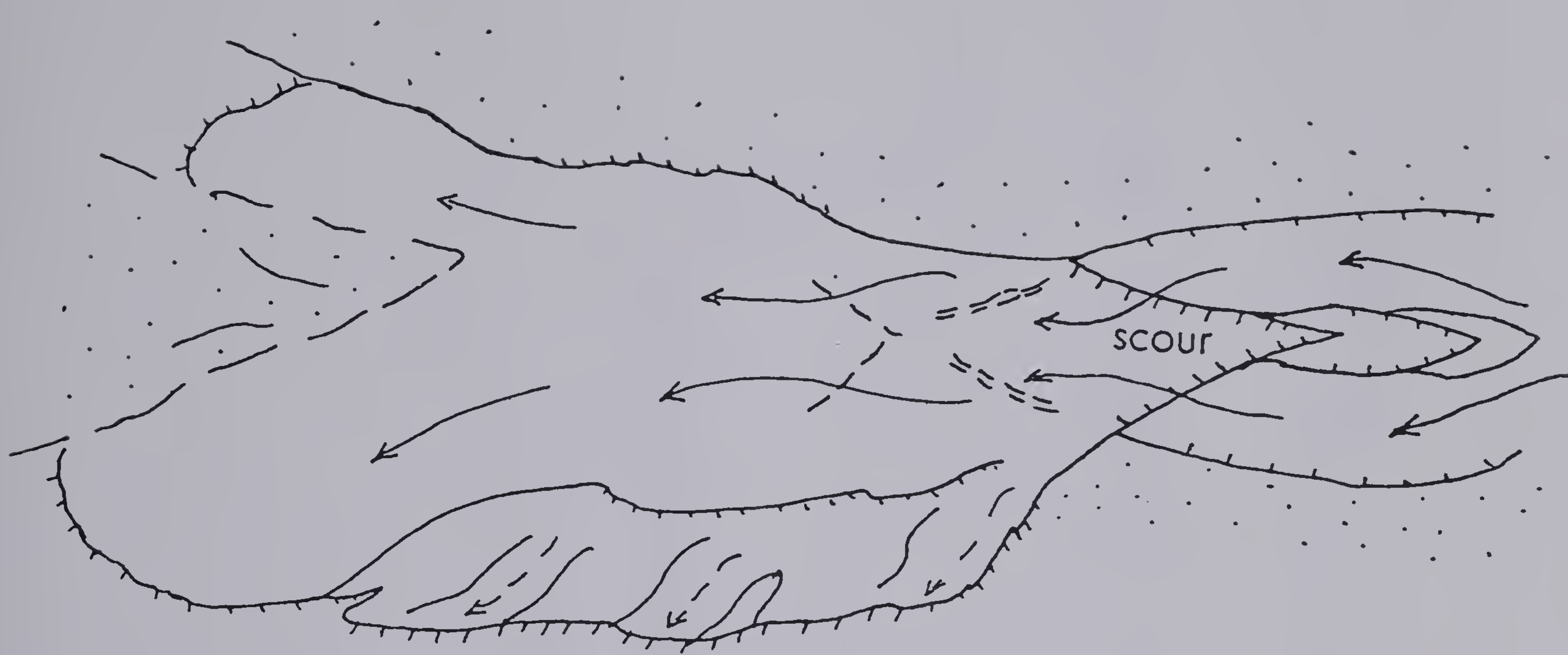

scour

version of the dissection and abandonment of individual bar lobes. But, observations over extended periods of time suggest that there is higher order of activity, on the scale of the wavelength of bends and complex flats, which produces alternate aggradation and degradation both in a spatial dimension and through time at any one point. Fig. 4.27 shows one manifestation of this in the form of a larger fan-like deposit with several small channels and chutes beginning to dissect its surface and compete for dominance. These zones of aggradation and degradation alternate downstream and shift downstream in the same way bars migrate down the channel. Any one zone may experience alternate aggradation and degradation through time and this may be expected to produce consistent fluctuations in sediment yield over a given length of time and Fig. 4.28 shows a typical sediment yield curve for one 35 hour period. The evidence presented by Church (1972) for the existence of a stepped profile on sandur surfaces may be a further manifestation of this higher order process. The length of the flume was insufficient to identify any such regularity in the long profile.

4.4.6 Rates of movement

No attempt was made to obtain detailed information on the rates of operation of various processes but observations and time-lapse photography provided some general figures with which published data may be compared. It should be remembered that flume processes operate continuously at channel-forming flow which is not the case in natural rivers. However, the natural processes are active only at high flow periods and the flow in the flume can be thought of as a series of such high flow events strung together. Generally, processes operate

Figure 4.27 Large fan complex. Downstream of scour pool developed in a fan-like form from a series of bars and channels migrating across the surface.


scour

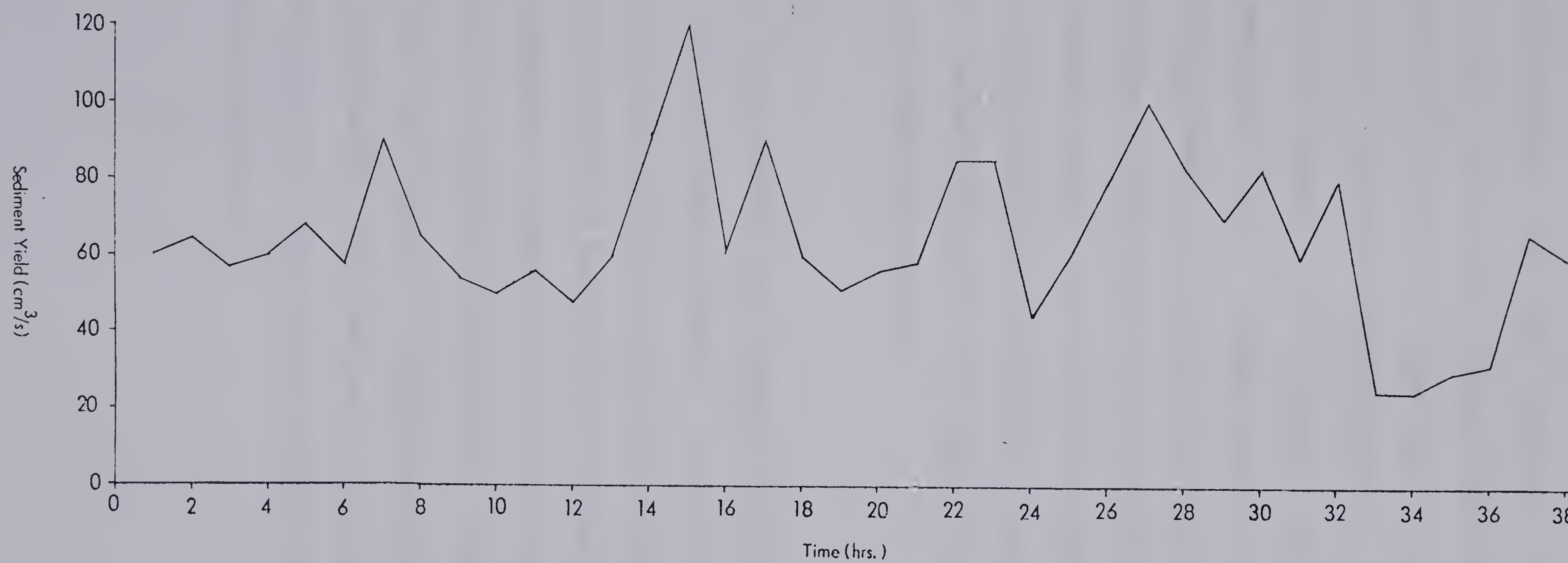


Figure 4.28 Fluctuation of sediment delivery to tail-box over several hours.

on at least two time scales. Small scale features - bars and scour holes - form and decay in only a few minutes. Typical migration rates for foreset bars are of the order of 0.5 cm/min. These compare with observations by Hein (1974) of small scale bar changes occurring in 3-6 hours at high flow and migration rates of 1.22-4.18 cm/min. With a scale ratio of 50-100 processes should occur 7-10 times faster in the flume (see Chapter 3) and the approximate rates quoted above agree reasonably well with this. In the same way the larger scale bar developments which take place over several hours in the flume might be expected to take several days of discontinuous flood discharges in a natural river. There are no data available to confirm this extrapolation, or to accurately estimate much longer-term form evolution.

4.5 Conclusions

Thus, by understanding the interaction of bars and channels and by recognizing a series of basic processes it is possible to reach some conclusions as to the construction of larger scale features. It has been shown that the tendency of the channels to deposit large bedforms, as a result of fundamental instability or a change in local flow conditions, leads to the development of braiding. The active lobate bars and associated scour holes are at the core of the development of braiding and an understanding of the sedimentary processes involved in their formation could go a long way to developing a general model of braided river sedimentology.

CHAPTER 5. SEDIMENT SORTING

5.1 Introduction

Because of the complexities of braided rivers description and explanation of the detailed distribution of sediment size within a reach is problematical. General downstream relations in gravel outwash are well known but surprisingly little data exist on local sorting patterns. Where such patterns have been identified their explanation has proved difficult partially because rarely is it simply a case of a difference in critical shear stress for different grain sizes. A brief summary of some principles of sediment transport will aid in an understanding of the later discussion.

5.2 Aspects of Sediment Sorting

In gravel bedded braided streams it is apparent that a large proportion of the sediment load is carried as bedload (*e.g.* Church, 1972, gives figures of 80 percent by volume of the total load). The bedload consists of a mobile carpet of grains of a range of sizes rolling, sliding and saltating along the bed. Even with a large size range there is very little difference in the critical tractive force for a large proportion of the bed material so that there is a tendency for a large portion of the load to move at the same time.

The problem of the initiation of motion has been approached in two different ways. The analytical approach of White (1940) considers the equilibrium of a single grain with respect to two forces - a fluid force tending to entrain the grain and a gravitational force resisting entrainment. It is assumed that both act through the centre

of gravity of the grain but the grain will move by pivoting round a fixed point. Thus, the analysis involves consideration of the balance between two moments rather than forces. The shear stress needed to initiate the motion of a grain therefore depends not only on the size of the grain and its submerged specific weight but also on the angle of pivot and hence on its exposure.

The second experimental approach is exemplified by the results of Shields. His results are usually displayed in the form of a diagram of the ratio of shear stress and gravitational force versus the boundary Reynolds number ($Re^* = \frac{d\ u^*}{\upsilon}$). The boundary Reynolds number is effectively an expression of the grain size in relation to the thickness of the viscous sublayer and is important in the drag and lift acting on the grain.

Both these approaches use the same variables and both produce the same basic result. Thus Shields' criterion can be converted to a straightforward plot of grain size versus shear stress and the two are almost directly proportional (Blatt *et al.*, p. 91, Fig. 4.6). However, many field studies of sediment motion have suggested that Shields' criterion is by no means completely reliable and actual values of critical shear stress may be a factor of four either side of the value predicted from Shields' relationship. The reasons for these variations lie, firstly, in the effect of sediment sorting and bed configurations on the exposure of grains and the critical shear stress. Also, initiation of motion depends on instantaneous values of shear stress which may be four times greater than average values. Church (1972) has also pointed out the effect of the state of the sediment on the critical shear stress. Underloose (or armoured) material will require higher shear stresses than

predicted while overloose sediment will experience motion at lower values of critical shear stress than predicted from Shields' criterion. In fact the definition of the condition of the commencement of transport is perhaps the greatest problem. Note, also, that on a steeply sloping surface initiation of motion will occur at much lower shear stresses than indicated by Shields' criterion because of an added gravitational component, and once material is in motion transport will continue on a flat surface.

In fact, conditions may be so different from those involved in the theoretical and simplified experimental approach that under some circumstances the relationship may be turned upside down and larger grains will move more readily than the smaller ones. This arises from the influence of the angle of pivot of the grains and also from the fact that shielding of smaller grains by larger ones may occur. In particular, where large grains rest on a bed of smaller particles, their angle of pivot may be much lower than that for the smaller grains and they may, therefore, be moved more easily. Chang (1939) proposed a second and rather different explanation for this phenomenon in which he demonstrated that the larger grains may be exposed to a higher velocity because they project further into the flow. The effect of this difference in velocity may exceed the effects of the difference in critical shear stresses for the two particles and produce motion of the larger grain at lower mean velocities than the smaller one. Straub (1935) observed the preferential movement of larger particles in flume experiments in which a size gradation from fine to coarse developed downstream during the experiment. Russell (1968) quotes Byrne (1965p) from wind tunnel experiments on the detachment of grains 0.3-0.65 mm

in diameter, in which he concludes that: "...The exposed, larger particles in the distribution are the most unstable and will be the first to move as the surface drag is increased."

Similarly, Everts (1973) refers to the tendency for larger grains to move more easily over a fine bed than grains of the same size as the bed, and Church and Gilbert (1975) report several other cases of the preferential movement of coarser grains under certain circumstances.

Not only is it possible for the coarser grains to be mobilized first but once in motion they will move at higher velocities (Meland and Norrman, 1966, 1969). On a fixed bed there is a direct relationship between particle size and velocity but on a mobile bed where other factors, notably bed stability (*i.e.* the ability of the bed to support the larger particles), play a role, the maximum velocity occurs in the coarser sizes but below the maximum size range. Meland and Norrman (1966, 1969) emphasized the importance of sorting which occurs while the load is in transit and point out that the greatest amount of sediment transport occurs at velocities well in excess of critical for all compoenent sizes hence diminishing the importance of processes such as winnowing out of fines at velocities below critical for the larger grains. In addition Meland and Norrman (1969) pointed out that sorting in a vertical plane may also occur during transport. Thus the very finest grains tend to filter down through the interstices into the lower layers. At the same time the largest grains tend to fall into low points on the bed such as dune troughs and also to move at the base of a traction carpet because of inadequate support offered by the bed.

In explaining observed sediment sorting patterns it is necessary to be aware of and to make use of these observations.

5.3 Sorting in Braided Rivers

The literature on braiding has tended to be oriented towards to types of grain size analyses. The first considers the general sorting pattern on the surface of outwash fans (*e.g.* Church, 1972; Boothroyd and Ashley, 1975) and the second, geological, approach has tended to emphasize gross vertical changes in grain size rather than localized within-unit horizontal and vertical trends. Generally, grain size distributions in braided rivers are highly complicated and characteristically show abrupt transitions from one size to another. However, recent studies have recognized some order in the apparent chaos. Note that we are referring only to sorting in the gravel size range because sand and silt, although important to the detailed sedimentology, were not represented in the flume river.

The most important studies of the sorting of grain sizes in gravel braided rivers have been by Hein (1974) and Smith, N.D. (1974) . Krigström (1962) and Bluck (1974, 1976) do make some reference to sorting patterns but the majority of studies have tended to concentrate on grain characteristics others than size, such as orientation.

The data available refers largely to sorting on the surfaces of transverse bars which compose a large proportion of gravel braided river deposits. Both Hein (1974) and Smith, N.D. (1974) found fairly consistent downstream-fining and upward-fining within well-developed transverse bars. Trends on bars oblique to the flow are not as clear but Hein (1974) suggested that the size distribution may be governed by the slope of the bar in this case. Bluck (1974, 1976) observed that many

complex bars show an upstream (bar head) gravel deposit with an abrupt transition to a downstream sandy tail. For gravel meandering rivers McGowan and Garner (1970) found very poor sediment sorting on chute bars, which they suggested was the result of rapid deposition during periods of high activity.

While many active unit bars and single stratigraphic units within braided deposits show fining upwards (Williams and Rust, 1969; Rust, 1972; Eynon and Walker, 1974; Hein and Walker, 1974; Smith, N.D., 1974) coarsening upward units have also been identified. Thus Hein (1974) presents data showing as many coarsening-upward and fining-upward sedimentary features, while 50 percent of exposures show no obvious size trends at all. The coarsening-upward sequence described by Costello and Walker (1972) from palaeo-outwash involves several units and is therefore of a rather different type than the single bar trends.

Explanations of the trends observed have relied largely on differential transport and winnowing of finer sediments (Hein, 1974) although Smith, N.D. (1974) has proposed three possible mechanisms by which the fining trends of transverse bars might be produced:

1) Lateral migration of gently dipping bar margins which show a trend from fine to coarse from top to bottom.
2) Waning discharge.
3) Migration of avalanche faces which show fining upwards. Such fining upwards is a well-known phenomenon but depends apparently on the rate of supply of sediment (Blatt *et al.*, 1972). The slower the rate the better the sorting.

5.4 Sorting Observed in the Model

The size distribution data collected from the flume were used with the intent of:

1) comparing the patterns with those described from natural braided rivers.
2) describing any other consistent trends in size.
3) testing the feasibility of proposed sorting mechanisms.

Unfortunately the third of these objectives was restricted by the fact that the depth of flow over the bars made the use of a pitot tube of a suitable size impossible hence no useful quantitative data on flow over the bars was obtained.

5.4.1 Bars

The data for the sorting on transverse bars consist of 7 pairs of samples from centre of the upstream end and the downstream margin of the bars, an eighth sample including samples from the edge, middle and base of a bar, and two pairs of samples (one from an avalanche face and one from the interior of a bar) to illustrate the vertical sorting trends.

Fig. 5.1 summarizes the results of the analysis of the downstream fining trends. There is a clear difference in both size and sorting between the upstream coarser samples and the finer downstream samples. A useful non-parametric statistical test for establishing whether there is a significant difference in the means of the two populations from which the samples were taken is the Mann-Whitney U-test. It involves ranking all the values from both samples, assigning each to their respective sample and counting how many of the values of one sample precede each of those of the second sample. The test shows

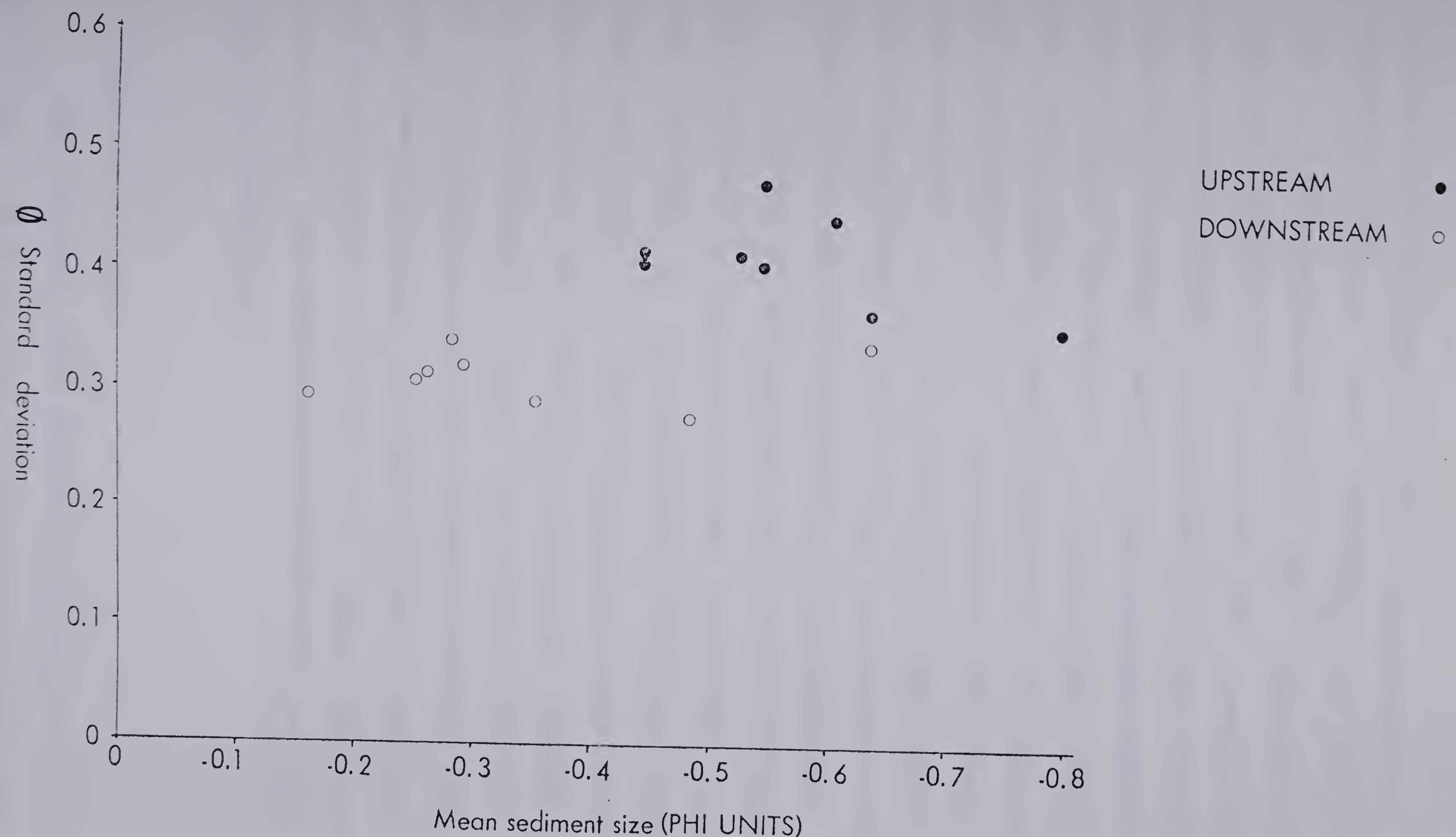


Figure 5.1 Changes in mean grain size and sorting in a downstream direction on bar surfaces.

that when treated as a group, the means of the downstream sample are significantly smaller (at the 0.05 significance level) than those of the upstream sample. All the downstream samples are better sorted than the upstream samples while skewness shows no discernible trend. However, when treated as pairs (upstream and downstream for each bar) six of the eight bars showed the downstream sample to be more negatively skewed than the upstream sample. When plotted on the same mean versus sorting diagram as the channel samples the upstream samples plot in the same area as the channel samples (Fig. 5.2). Notice that most of the channel samples are coarser and less well-sorted than the sieve sample of the sand introduced to the flume which indicates the presence of a coarse pavement in the channels not apparent except from measurements.

The vertical sorting patterns show a trend towards better sorting and lower mean size upwards on both avalanche faces and within the bar (see Table 5.1). The sorting within the eighth bar follows the pattern drawn in Fig. 5.3. While fining upwards is evident at both the head and the tail, there is a coarsening downstream at the base rather than the fining apparent in Smith's (1974) diagram (his Fig. 15). However, the problem is that it is very difficult to be certain that the samples taken within the bar are indeed at its base. Notice also that the fining downstream at the surface is only evident on the downstream half of the bar. The transverse bars therefore follow the trends presented in natural rivers.

5.4.2 Scour Pools

Hein and Walker (1978) stated that following a period of high discharge only a coarse lag remained on the surface in scour pools.

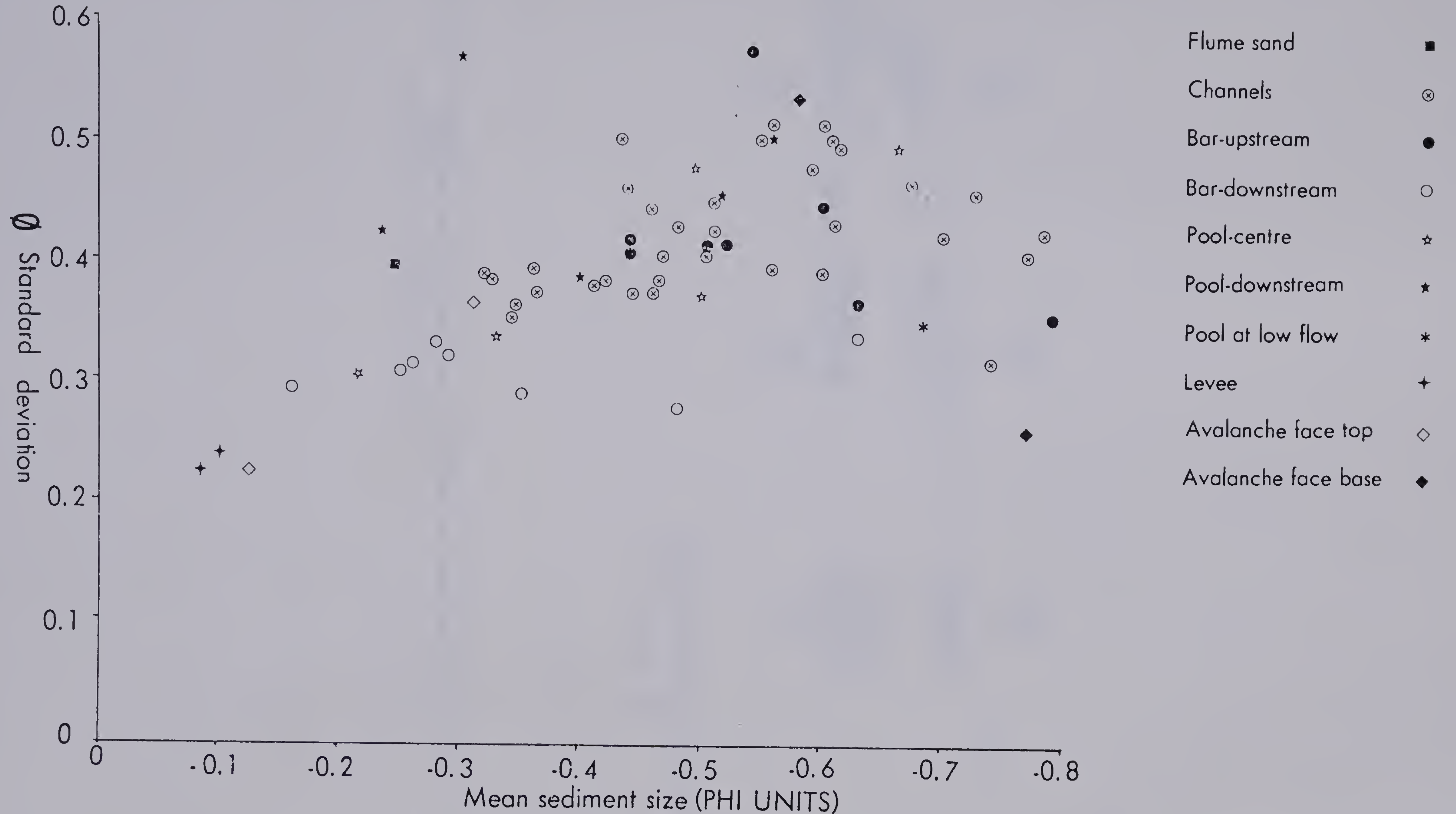


Figure 5.2 Median grain size and sorting for all sediment samples.

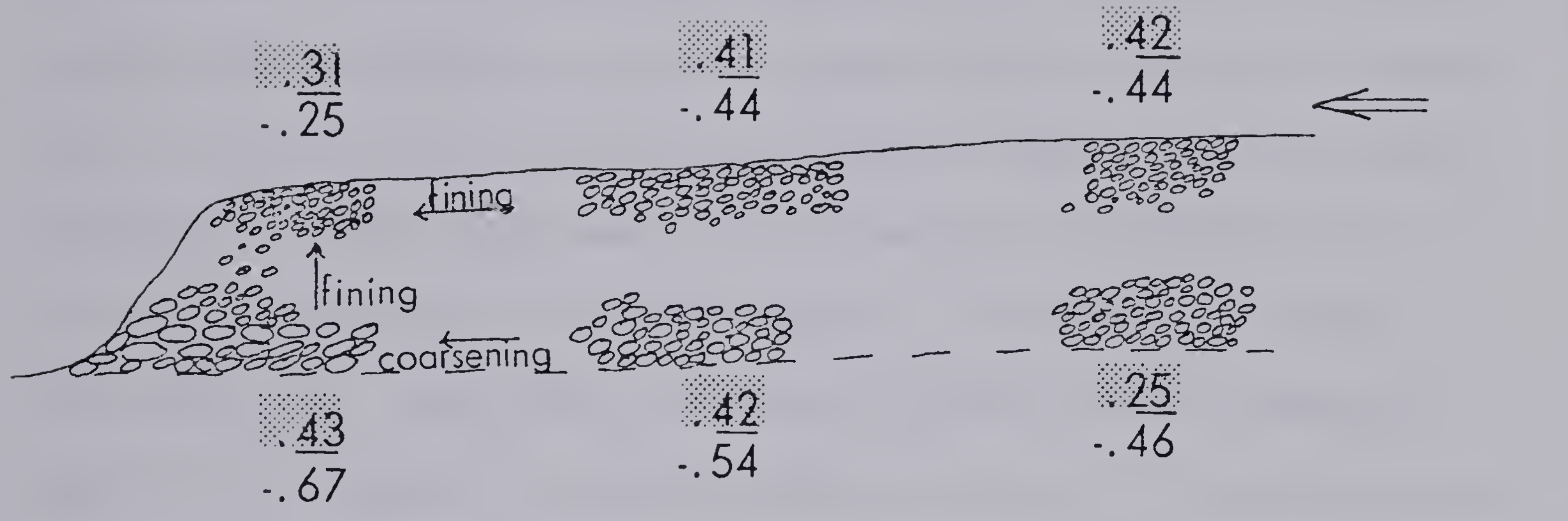


Figure 5.3 Vertical and downstream changes in mean grain size and sorting on individual bar.

In order to test whether this lag developed while the scour holes were fully developed, 5 pairs of samples from pools and the channels immediately downstream were taken from active channel junction scours. One further sample from a scour during waning flow was also taken.

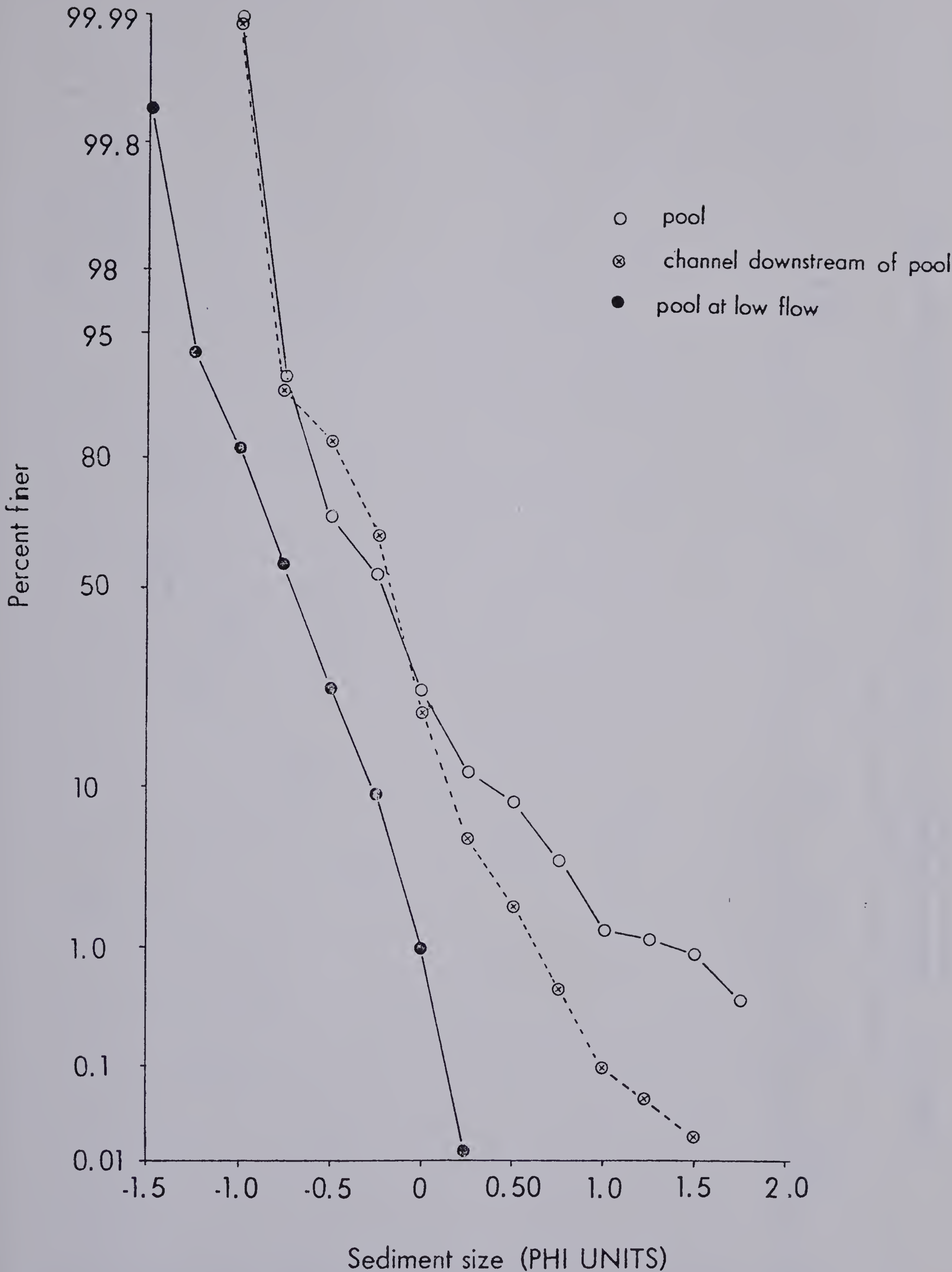
The cumulative curves from the pools and channels seem to plot very close to each other (Fig. 5.4) and U-tests showed no significant differences in means, sorting or skewness between the two groups of samples. However, pair-wise comparisons are suggestive of better sorted and more negatively skewed channel samples although the sample size is far too small to give any conclusive results in this respect. Therefore, at peak flow there is no evidence for the development of a lag in the pools but the low flow sample is significantly coarser (see Fig. 5.5). One point of interest evident from the cumulative curves but not brought out by the sample statistics is the presence of a very fine tail making up only a 3 or 4 percent by weight of the pool samples but representing a large portion of the sample by number. Such grains are almost entirely absent from the downstream samples and from other channel samples.

5.4.3 Other Patterns

Additional miscellaneous samples revealed grain size distributions of interest:

1. Lateral sorting on levees - samples from the edge of one bar, the margin of a channel and from the 'levees' downstream of scour holes showed the sediment in these areas to be significantly finer and better sorted than the channel samples (see Fig. 5.2 and entry 3, 4, 5 in Table 5.1).

Figure 5.4 Cumulative grain size curves for typical scour pool at full and declining flow, and for channel immediately downstream.


99.99
99.8
98
95
80
50
10
1.0
0.1
0.01
Percent finer
pool
channel downstream of pool
pool at low flow
-1.5
-1.0
-0.5
0
0.50
1.0
1.5
2.0
Sediment size (PHI UNITS)

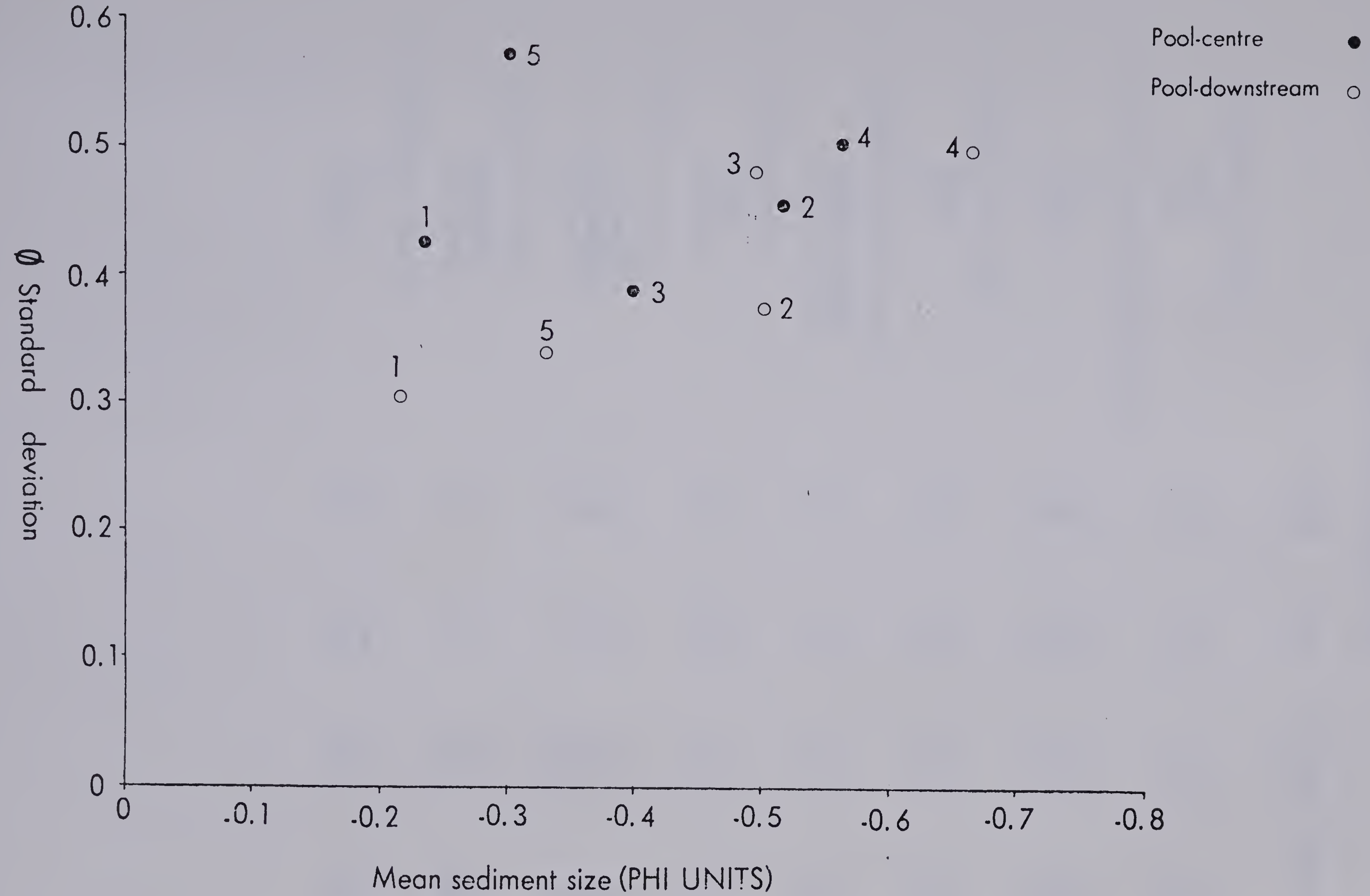


Figure 5.5 Pairwise comparisons of mean grain size and sorting for pools and adjacent channels.

TABLE 5.1 Miscellaneous Sorting Data

	Median (ϕ)	Mean (ϕ)	Sorting (ϕ)	Skewness
1. Avalanche Foreset				
TOP	-.24	-.313	.365	-.481
BASE	-.80	-.770	.261	+.434
2. Vertical Sorting Within Bar				
TOP	-.12	-.127	.225	-.112
MIDDLE	-.19	-.183	.229	+.062
BASE	-.55	-.583	.537	-.053
3. Waning Flow Scour				
LEVEE	-.11	-.100	.240	+.128
POOL	-.78	-.663	.265	+.635
4. Channel Junction Scour				
CHANNEL CENTRE	-.39	-.493	.479	-.32
CHANNEL MARGIN	-.32	-.343	.360	-.186
5. Channel/Levee				
LEVEE	-.09	-.083	.225	+.049
CHANNEL	-.40	-.43	.357	-.123
6. Channel Division				
L. CHANNEL	-.525	-.518	.356	+.078
R. CHANNEL	-.40	-.48	.349	-.358
CENTRE	-.90	-.88	.310	+.259
7. Abandoned Sheet				
UPSTREAM	-.35	-.40	.377	-.269
DOWNSTREAM	-.85	-.81	.346	+.256
8. Abandoned Channel				
BAR	-.78	-.740	.358	+.274
CHANNEL	-.16	-.138	.335	+.046

2. Channel division - samples from the upstream area of exposed bars showed a veneer of sediment much coarser than that of the adjacent channels. Observations suggest that this is a feature developed after channel division has occurred (entry 6, Table 5.1).
3. Waning flow - as flow declines over a surface there may be a tendency for the larger grains to move more easily and collect at the downstream margins of thin gravel sheets (entry 7, Table 5.1).
4. It is common, particularly as flow declines, for a bar consisting of material much coarser than the channel material to be deposited within the channel producing a coarsening upward trend. There is no evidence that this occurs consistently, rather it depends very much on the local circumstances, particularly the material available (entry 8, Table 5.1).

It is these patterns which seem to show more clearly the result of the preferential movement and higher velocity of coarse material.

5.5 Sorting Mechanisms

In the absence of measurements, much of what follows must be of a speculative nature.

5.5.1 Bars

Although the downstream fining trends were well established, Hein (1974) failed to demonstrate convincingly that there was a winnowing out of fines from the bar head deposits (or diffuse gravel sheets) and deposition immediately downstream. Measurements of shear velocity and estimates of shear stress showed no consistent trends downstream and attempts to apply Shields' criterion to stationary and

moving grains proved unsatisfactory. Nevertheless, Hein (1974) proposed that the upstream deposit was indeed a lag while "differential transport" could also play a role in the sorting mechanism. Apart from this, she does not account for the fining-upward evident in many bars. Smith's (1974) suggestion that a decline in discharge may be important remains a possibility although in the flume sorting was observed over bars in which discharge was apparently fairly constant. We are left with one remaining cause, fining-upward avalanche faces. Since the transverse bars show well developed avalanche faces the samples collected from their downstream margins will be taken from the tops of foresets and indeed the two types of samples fall in the same region of Fig. 5.2. The fact that the fining trend only begins in the downstream part of the bar (see above) may also be significant. Perhaps what we are seeing is a tendency for all sizes to move across the bar and to avalanche down the avalanche face but the coarse grains congregate at the bottom of the face while the finer material is trapped higher up. If the avalanche face increases in height as the bar develops then sorting may only begin once the face has reached a given height *i.e.* after the bar has extended some distance downstream. Samples from the bases of avalanche faces show that the coarsest material reaches those areas so that its absence on the bar surface is not caused by a failure to be moved from the bar head region. Clearly, further sampling is needed to confirm this. However, this does not explain the progressive downstream fining on Smith's (1974) bars (see his Fig. 11, p. 216). Unfortunately, there is no indication as to whether these bars have avalanche faces or not and his general model of sediment sorting (Fig. 15, p. 219) contains no indication that avalanching is responsible for

the pattern illustrated. Thus, while proposing sorting on avalanche faces as a possible mechanism, he produces no evidence to test the idea and apparently favours other mechanisms in many cases. But, the vertical sorting mechanism remains a reasonable explanation of downstream fining on some bar lobes at least.

5.5.2 Pools

As mentioned previously it seems that a coarse lag only develops in scour pools during the waning flow stage. During peak flow the pools are apparently competent to transport any material which may be transferred into them. The lag may be covered by finer material as refilling occurs. Recently there has been some discussion as to why the pools and riffles of meandering rivers should show finer and coarser bed material respectively, while under most flow conditions velocities are lower in pools than riffles (see, for example, Keller, 1971). The explanation appears to lie in the greater competence of pools at high discharges allowing the removal to the next riffle of any material introduced from a riffle upstream. The meander pool and scour hole of the braided river appear to be similar and therefore excavation of meander pools in gravel may reveal a coarse lag immediately above the scour surfaces.

In fact, the fine tails of the pool samples suggest that it is the very fine material which is trapped in the pools, not the largest grains. Alternatively, the fine material may be sediment which has been progressively washed to the lower layers in the deposits and is only exposed in deep scours.

5.5.3 Lateral sorting

The trends described on channel levees, channel division and exposed surfaces may be explained by two related mechanisms. These are exemplified by two sorting patterns: the fine levee deposits and the coarse veneer at exposed bar heads and in the early stages of avulsion. The two are a response to the fact that the larger grains have greater inertia and move more easily over finer surfaces and also to the lateral balancing mechanism commonly used to account for fining-upwards across point bars.

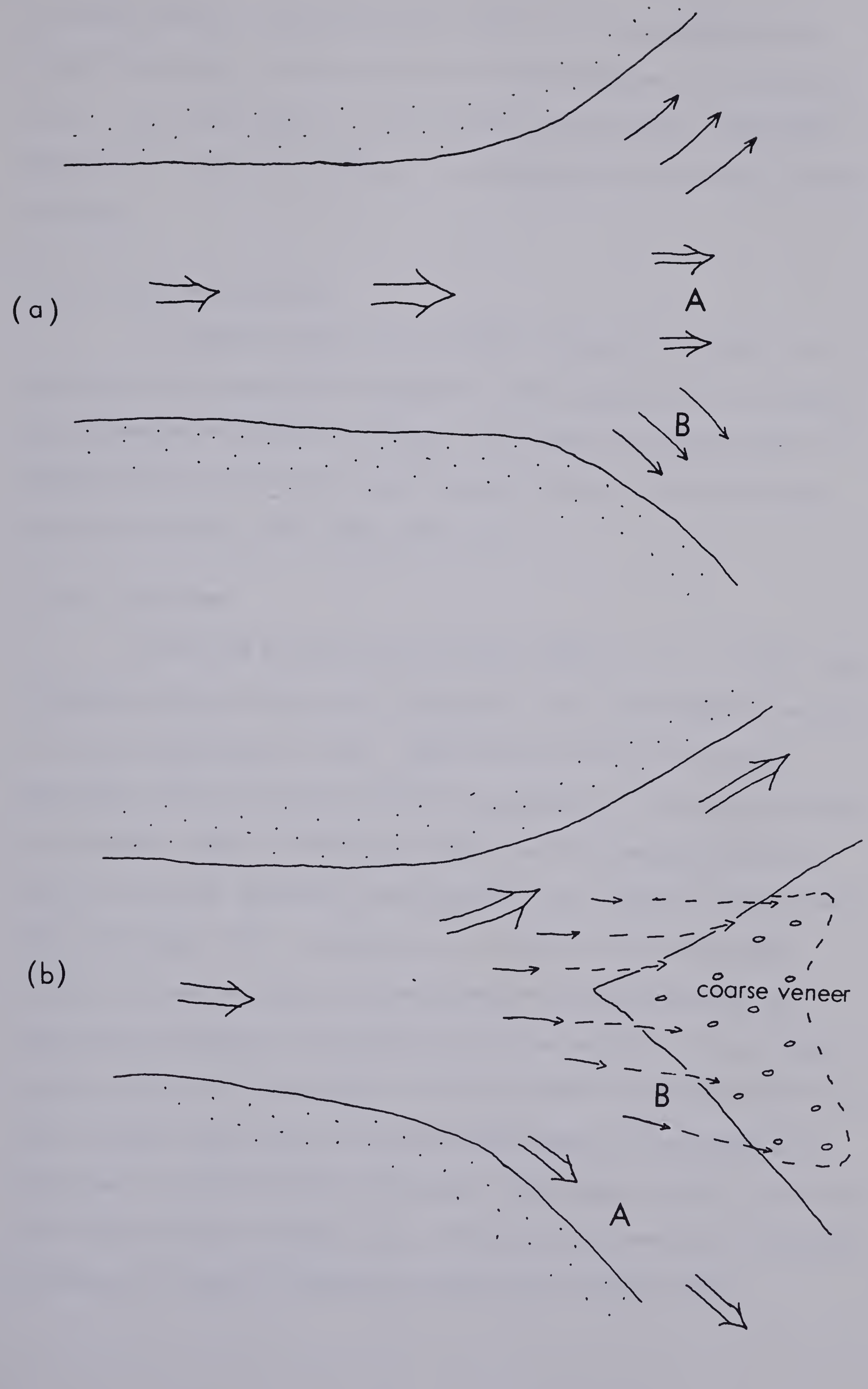
We can envisage two situations in which these properties may be significant. Whenever the main flow continues in an approximately straight line, but where weaker secondary currents might exist along the bed away from the main current, we might anticipate that the smaller grains with a lower inertia will be more susceptible to transport by the weaker divergent current (Fig. 5.6a). Thus where flow expands (on a bar), or a secondary current develops (downstream of scour pools) fine material will accumulate either as distinct ridges or as gently sloping benches. The fact that the smaller grains are lighter also allows them to be transported higher up onto the levee than the larger grains.

Where the main flow turns the finer grains may be more easily taken with the current while the larger grains with a greater inertia will be turned less easily and may become trapped in shallow water on the outside of the bend (Fig. 5.6a). Thus, where a channel division occurs the coarse material may run up onto the bar head in between the channels while the fine material continues downstream. Similarly if

Figure 5.6 Lateral sorting mechanisms.

(a) In flow expansion.

(b) In bends.


(a)
A
B
(b)
coarse veneer
B
A

avulsion occurs at the outside of a bend it is the coarse material which will overtop the banks first and travel farther in the shallow flow. Thus, a difference in the way grains of different sizes react to given flow conditions is central to the explanation of several sorting patterns.

5.5.4 Abandoned surfaces

In shallow waning flow secondary sorting of material as a result of the preferential movement of coarse grains is also evident. Thus, abandoned surfaces show sheets with coarse downstream edges and channels may be filled with coarse material because it is the only material in motion under these conditions.

5.5.5 Antidunes

With flow at fairly high Froude numbers (1-1.3) in many flume channels antidunes occur quite frequently. Their amplitude is usually 2-3 mm and wavelength 1-2 cm. Antidunes are common in braided rivers but the only evidence of their preservation is the observation of transverse ribs of alternating coarse and fine sediment found on some bar surfaces (McDonald and Banerjee, 1971; Gustavson, 1974; Boothroyd and Ashley, 1975). Because of the delicacy of the antidunes sediment collection from the flume examples proved impossible but observations suggested the presence of coarse material in the troughs and fine material on the crests. If this pattern is preserved then transverse ribs could indeed result but it is probable that most of the examples of this type of sorting would be destroyed. This does, however, serve as a good illustration of another way in which vertical sorting of sediment may occur, in a manner suggested by Meland and Norrman (1969).

5.6 Conclusions

This brief investigation of the areal sorting of sediment in the flume channel has shown, first, that even at this scale significant differences in grain size occur from place to place across the river and that in general terms the sorting patterns observed follow those of full-scale rivers. Thus the transverse bars approximate the Hein (1974) and Smith, N.D. (1974) models, although there is some questions as to whether the basal layers fine downstream. In addition, the development of a coarse lag in pools on the falling stage is indicated and the importance of secondary currents and the different properties of grains in transport have been shown to be important in the development of some other consistent areal sorting patterns. In terms of mechanisms the Smith, N.D. (1974) model of fining-upward avalanche faces seems to be the most probable explanation of the trends found in transverse bars while in this and other instances an emphasis must be put on either preferential motion of coarse particles or differences in response of different sizes to the flow conditions. What is most surprising is that clear size sorting patterns develop despite the very narrow range of grain sizes in the flume sand.

CHAPTER 6. CHANNEL FORM

6.1 Introduction

If the mechanisms by which river channels adjust to changes in discharge, sediment load, bed and bank material and slope can be understood it becomes possible to explain not only why a river should adopt a particular pattern but also to predict under what circumstances it will assume that pattern. In the past model studies have been used to demonstrate the existence of pattern thresholds related particularly to slope (Schumm and Khan, 1971) but if models are to be of use in quantifying these relationships it is important that the model channels bear a close similarity to natural channels of an equivalent slope, discharge and grain size. While the similarity should include aspects of sediment transport as well as channel geometry, data available from this study allow only similarity of the latter to be assessed. As self-formed stable channels these braided anabranches should adjust in precisely the same manner as natural braided anabranches and, when suitably scaled, data from model and prototype should coincide. The similarity of channel form is thus one stage beyond the process modelling discussed in the previous chapters.

6.2 Channel Flow

Before proceeding to a discussion of channel form it is important that the nature of the flow in these small channels be described in order to demonstrate that Reynolds numbers are in the turbulent range and that Froude numbers are close to those of natural, steep, gravel, braided channels. Data for all channels are presented in

Appendix 1 and a brief summary is given here.

Reynolds numbers for the flow as a whole were calculated using $Re = \frac{\bar{v}\ d}{\nu}$. Values range from 1300-3600 with a mean of 2203 and standard deviation of 536. Henderson (1966) indicated that in flow over a rough surface values of Re of approximately 10^3 are sufficient to give turbulent flow with only minor viscous scale effects (see, for example his Fig. 11-2, p. 492). The values obtained from the model channels therefore satisfy these conditions. Similarly, particle Reynolds numbers ($Re^* = \frac{u^*\ d_{90}}{\nu}$) are also high and can be ignored in terms of sediment entrainment. The range of values is 43-112 with a mean and standard deviation of 62.5 and 14.7 respectively. Inspection of Shields' diagram shows that these low values of Re* are likely to have only a minor influence on the entrainment function.

In open channel flow the Froude number is the most important flow relation and Froude similarity is the most important modelling criterion to be satisfied. Unfortunately data with which to compare the model results are sparse. Fahnestock (1963) gives values of Froude number which cover a large range, including supercritical flows. Rice (pers. comm.) reports that although Froude numbers in the proglacial Sunwapta River, Alberta, are below critical large standing waves are common at peak flow. Similarly, Fahnestock (1963) reports antidunes from the White River and other published photographs (*e.g.* Klimek, 1972; Boothroyd and Ashley, 1975; Church and Gilbert, 1975) suggest that flow near or above critical is not uncommon in these steep, shallow channels. Froude numbers from the flume channels range from 1.03-1.28, but in view of error in the measurement of depth and velocity, the accuracy of these values must be questionable. Nevertheless, the occurrence of standing

waves and antidunes in many channels (although never during measurements) suggest that these numbers are in the correct range. Thus, flow at channel forming discharges is apparently consistently at or above critical. The influence of the Froude number on channel form is difficult to establish but Rouse (1965) indicated that in the range 0.7-1.2 flow resistance related to the Froude number could be fairly significant (*e.g.* he recorded a 2-fold increase in resistance at critical values compared to those well below or above critical). The Froude number is clearly important under these circumstances but although the model values are fairly high they do not represent unusual conditions in nature.

6.3 Channel Shape

The anabranches all show similar cross-sections which consist of a flat bed occupied by a moving traction carpet of grains with concave upward banks (see Fig. 6.1). Width/depth ratios average 31.3 with a standard deviation of 10.1 and range from 11.9-64.6. This compares with White River data (Fahnestock, 1963) with an average of 24.5 and values from small sandur channels (Church, 1972) in the same range (15.6-67.9). This wide, shallow cross-section and flat bed are apparently a response to the non-cohesive material. Sundborg (1956), Lane (1957), Wolman and Brush (1961) and Schumm (1963) have observed that channels with a high bed load tend to show this form. Lane (1957) and Wolman and Brush (1961) indicated that, for an increasingly wide channel, the shear on the bed is increased at the expense of that on the bank. Thus, in non-cohesive material, at a given discharge, slope and flow resistance, the channel will widen until bank shear is

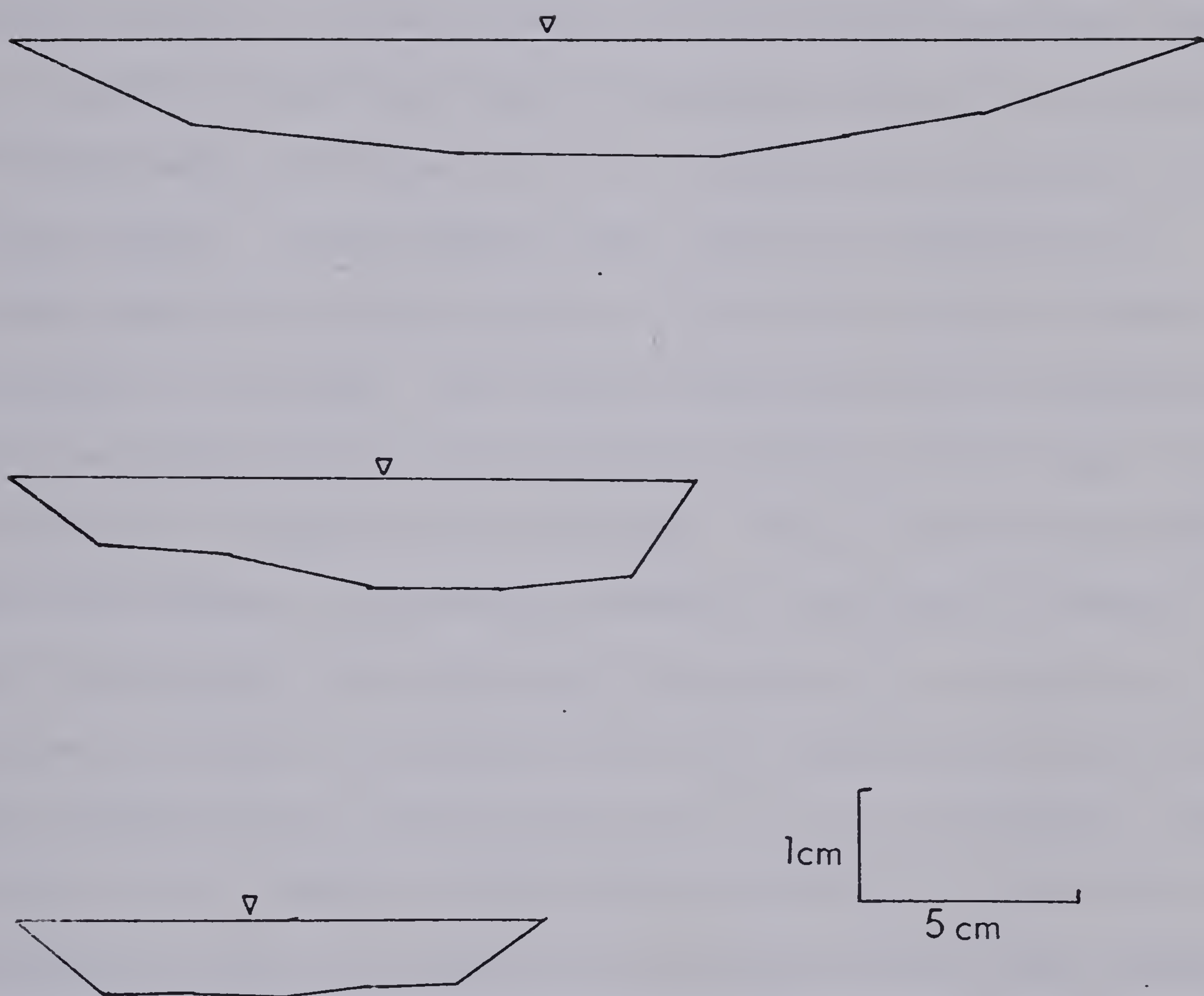


Figure 6.I Cross-sections of representative model anabranches.

insufficient to produce further erosion, at which point stability is reached. Parker (1978) has successfully derived regime equations for stable gravel channels with mobile beds using a theoretically derived bed-stress distribution based on the lateral transfer of momentum by turbulent diffusion. Pickup (1976) showed that from consideration of a standard sediment transport equation (Meyer-Peter, Muller) there is an optimum width, at a given discharge, at which bedload transport capacity is a maximum. Beyond this width the decline in shear stress resulting from decreasing depth counteracts the increasing load carried by the wider channel. In fact Gilbert (1914) apparently originated this concept when he discussed an optimum "form ratio" at which bed load transport is a maximum. In a similar vein Wilcock (1971) proposed that a higher width exponent in the hydraulic geometry favours a high rate of increase of competence with discharge. Thus, the geometry of these bed load channels is apparently a response to the nature of the bed and bank materials while the actual dimensions may be related to a tendency to adopt the "optimum or bed load transport maximising form at the discharge which, over time, the most bed load is transported" (Pickup, 1976, p. 371). However, in non-cohesive materials, at steep slopes, this tendency may lead to the adoption of width/depth ratios which produce channel instability and in-channel deposition.

6.4 Hydraulic Geometry

Since Leopold and Maddock (1953) first coined the term hydraulic geometry to describe the changes in width, depth and velocity with changing stage at a channel cross-section and downstream at a given discharge frequency, studies of hydraulic geometry have proliferated.

Now that a large amount of data exists Park (1976) and Rhodes (1977) have collected and organized this information in an attempt to identify differences in hydraulic geometry on a regional scale and also to explain the differences in exponents and demonstrate their importance on channel response to changing discharge. At the same time there has been some criticism of the procedure itself, centred particularly on the use of simple power equations for which there is no physical justification. Richards (1973, 1976), in particular, has advocated the use of polynomial equations while Lewis (1966) and Thornes (1970) both recognized non-linearities and breaks in data. In particular Lewis (1966) showed that it was not possible to fit a straight line to data covering a wide range of flows. Small channels with discharges less than 1 cfs. showed different exponents from the larger channels. Meanwhile attempts have been made to arrive at theoretical hydraulic geometries using a variety of approaches both, stochastic (Langbein, 1964) and physical (Smith, T.R., 1974).

The model channel data were collected on a random basis so that strictly speaking, they compare with neither at-a-station nor downstream hydraulic geometries. However, since all channels were sampled at channel forming discharge the data are of a form comparable to downstream hydraulic geometry, although the position of slope in terms of its dependence may be debatable. Fortunately, in addition to many published downstream hydraulic geometries, there exist some investigations of braided rivers in which data were collected in the same random manner as in this study (Fahnestock, 1963; Church, 1972; Rice, 1979) and these will form the basis of the comparison of model and prototype data.

The equations for standard hydraulic geometry obtained from

the model, using least squares regression are:

$$W = 0.47\ Q^{.619} \qquad r^2 = 0.65 \qquad \text{sig.} = .01 \qquad (10)$$

$$D = 0.144\ Q^{.261} \qquad r^2 = .404 \qquad \text{sig.} = .01 \qquad (11)$$

$$V = 14.53\ Q^{.12} \qquad r^2 = .291 \qquad \text{sig.} = .01 \qquad (12)$$

T-tests of the constants and exponents showed significance values of 0.01 also. The data and regression lines are plotted in Fig. 6.2. The relationships between discharge and slope and discharge and flow resistance (Darcy-Weisbach ff, Fig. 6.3) were not significant but the equations are as follows:

$$S = .0148\ Q^{-.039} \qquad r^2 = .00136 \qquad (13)$$

$$ff = .289\ Q^{-.24} \qquad r^2 = .0324 \qquad (14)$$

The scatter on all plots is very noticeable and is probably the result of both measurement error and the influence of variables other than discharge. But, attempts to improve the r^2 values using slope and grain size gave little improvement in the level of explanation. The failure of slope to improve the r^2 values is particularly surprising but as indicated previously the slope measurements were subject to considerable error. As a simple descriptive and comparative device the power equations are adequate for our purposes. Although more complex relationships between the variables may exist there is little justification for fitting more complex lines to the data in view of the scatter evident on the graphs. Also there are no published data with which to compare polynomial equations from the model with those from a prototype.

Table 6.1 summarizes the hydraulic exponents from other empirical and theoretical studies. While the low velocity exponent is common to most studies there are obvious differences in the partition

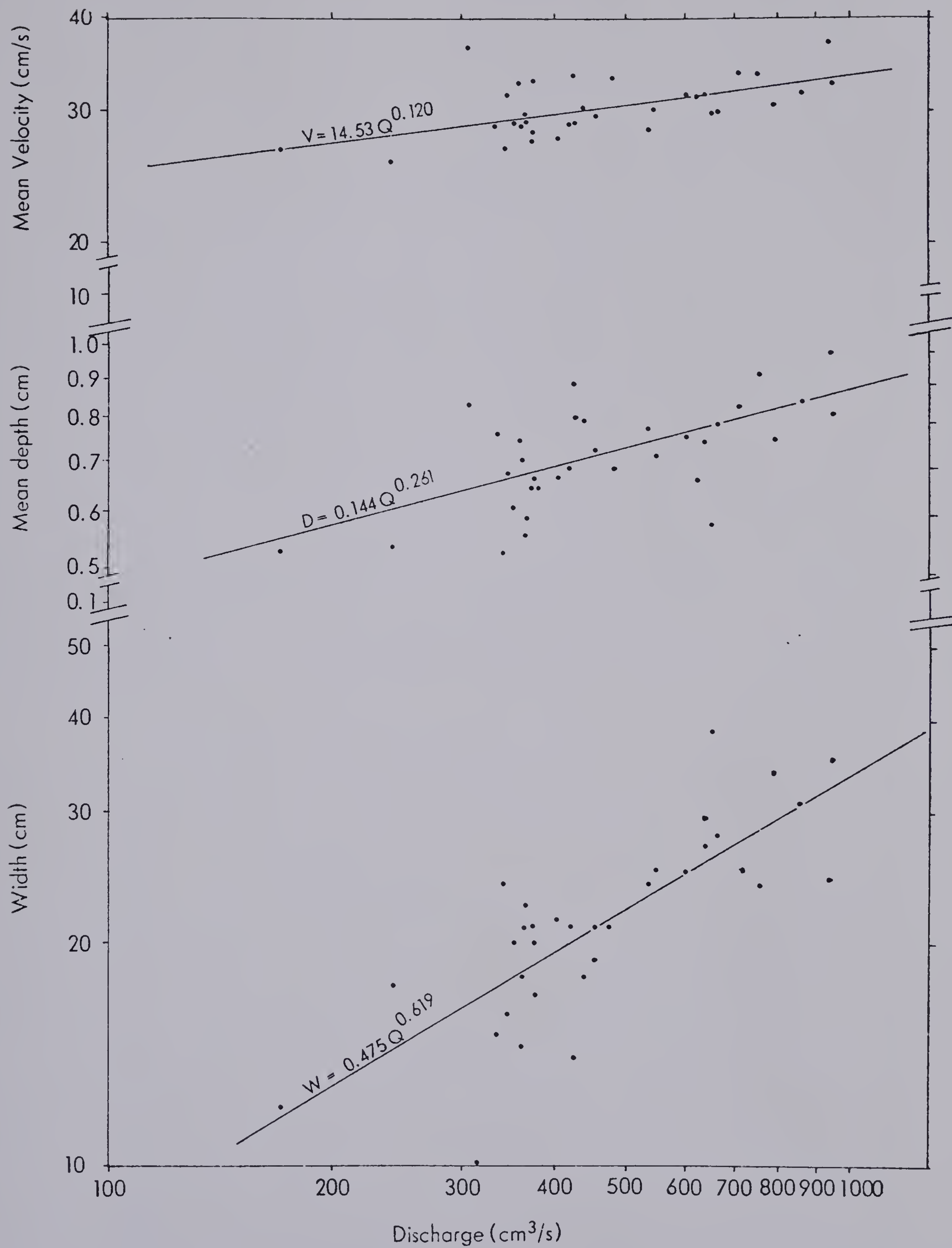


Figure 6.2 Hydraulic geometry of model channels.

Figure 6.3 Water surface slope and flow resistance (Darcy-Weisbach resistance factor) versus discharge for model channels.

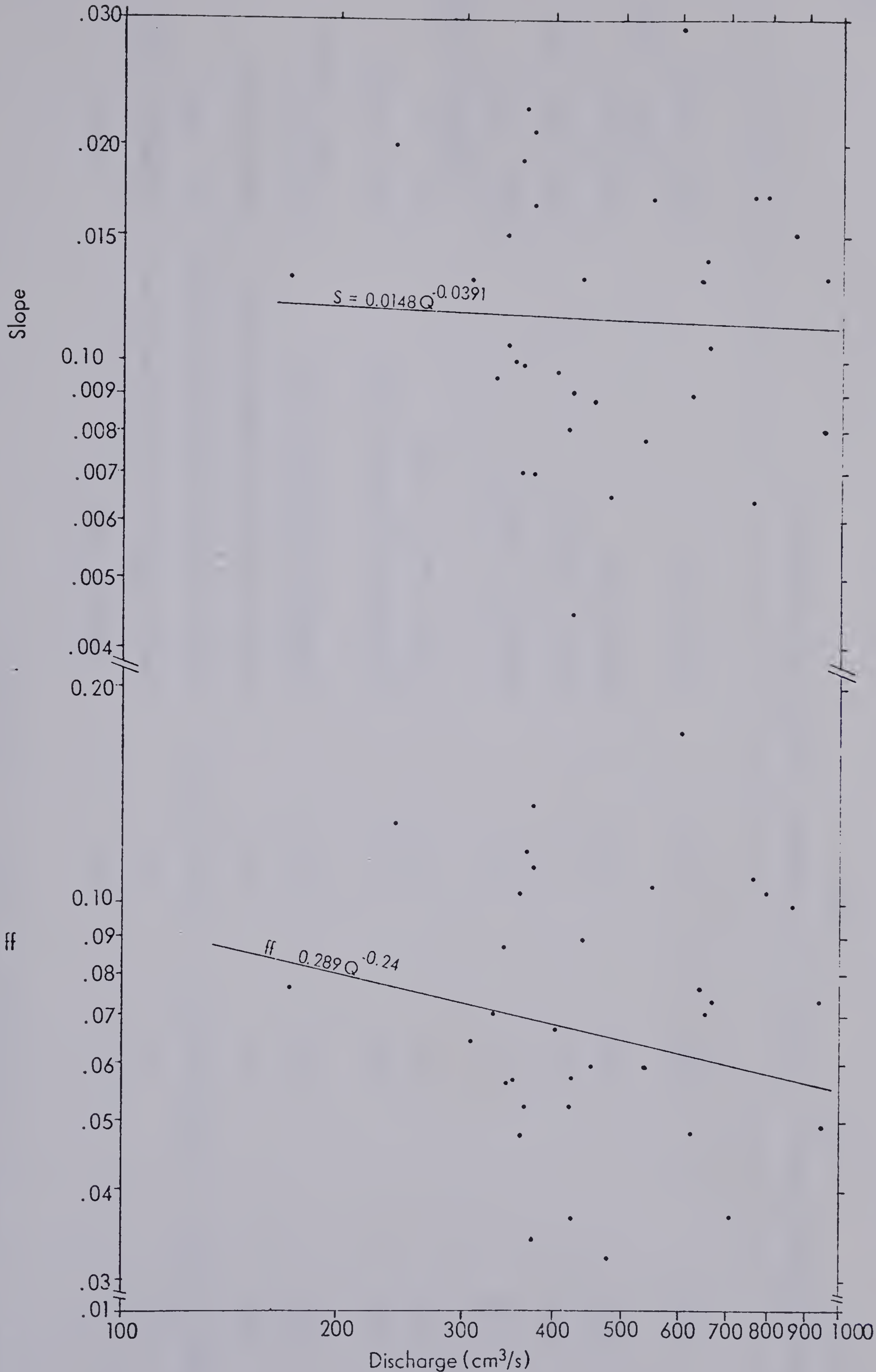

Slope
.030
.020
.015
$S = 0.0148\,Q^{-0.0391}$
0.10
.009
.008
.007
.006
.005
.004
0.20
0.10
.09
.08
.07
.06
.05
.04
.03
.01
ff
ff $0.289\,Q^{-0.24}$
100
200
300
400
500
600
700
800
900
1000
Discharge (cm^3/s)

TABLE 6.1 Summary of Some Published Hydraulic Geometrics

b	f	m	Type of Data	Source
0.38	0.33	0.27	random channels, proglacial gravel	Fahnestock (1963)
*0.39/0.47/0.45	0.28/0.25/0.36	0.23/0.20/0.15	random channels, proglacial gravel	Rice (1979)
0.64	0.17	0.19	random channels, proglacial sand	Church (1972)
0.50	0.39	0.16	laboratory channels, sand	Wolman and Brush (1961)
0.42	0.43	0.15	laboratory channels, sand	Ackers (1963)
0.51	0.36	0.13	stable canals, sand	Simons and Albertson (1963)
0.50	0.33	0.17	sand/silt canals	Lacey (1930)
0.50	0.40	0.10	gravel channels	Kellerhals (1967)
0.55	0.36	0.09	theoretical	Leopold and Langbein (1962)
0.60	0.30	0.10	theoretical	Smith (1974)

*Data from three areas of outwash fan, upstream, central and downstream.

$W = aQ^b$ $D = cQ^f$ $V = kQ^m$

of the increase in cross-section area with discharge. Generally speak- the agreement is close, with both empirical and theoretical downstream hydraulic geometries. The two comparable sets of data from proglacial gravel streams (Fahnestock, 1963; Rice, 1979) show lower width exponents than the flume channels but in general terms the flume channels show the same kind of hydraulic geometry, *i.e.* width exponents close to 0.5 or higher and velocity exponents 0.1-0.2.

A more useful exercise than the straightforward comparison of exponents can be carried out using the data from the Sunwapta River (Rice, 1979). These data were collected in a manner similar to the flume data, with adjustments made for measurements below bankfull discharge and for velocity measured using floats. Each reach was gauged at three stations and an average value for each parameter calculated from these three stations. Water surface slopes ranged from 0.002 to 0.016 (*i.e.* similar to those in the flume) and d_{50} from 8mm to 70 mm. By calculating dimensionless width, depths and discharges using d_{50} as the principle scaling factor it is possible to compare directly the dimensions of the model and prototype channels (Parker, pers. comm.). The three dimensionless varibles are defined as:

$$B^* = w/d_{50} \qquad (15)$$

$$H^* = D/d_{50} \qquad (16)$$

$$Q^* = \frac{Q}{\sqrt{Rp\ g\ d_{50}} \cdot d_{50}^{2}} \qquad (17)$$

Least squares regression for the model channels gave:

$$B^* = 3.66\ Q^{*0.505} \qquad r^2 = 0.638 \qquad \text{sig.} = 0.01 \qquad (18)$$

$$H^* = 0.37\ Q^{*0.34} \qquad r^2 = 0.636 \qquad \text{sig.} = 0.01 \qquad (19)$$

for the Sunwapta data:

$$B^* = 11.43\ Q^{*0.373} \qquad r^2 = 0.908 \qquad \text{sig.} = 0.01 \qquad (20)$$

$$H^* = 0.466\ Q^{*0.338} \qquad r^2 = 0.952 \qquad \text{sig.} = 0.01 \qquad (21)$$

and the two sets of data combined:

$$B^* = 8.16\ Q^{*0.404} \qquad r^2 = 0.89 \qquad \text{sig.} = 0.01 \qquad (22)$$

$$H^* = 0.395\ Q^{*0.352} \qquad r^2 = 0.926 \qquad \text{sig.} = 0.01 \qquad (23)$$

Figure 6.4 shows the two sets of data with their respective regression lines. Clearly there is considerable overlap of the data and, particularly in the case of the Sunwapta data, the position of the best fit regression lines may be affected considerably if part of the data is excluded from the regression. Thus, for example, using only points with Q* in the range 10^3-10^4 (*i.e.* covering the same range as the model data) produces:

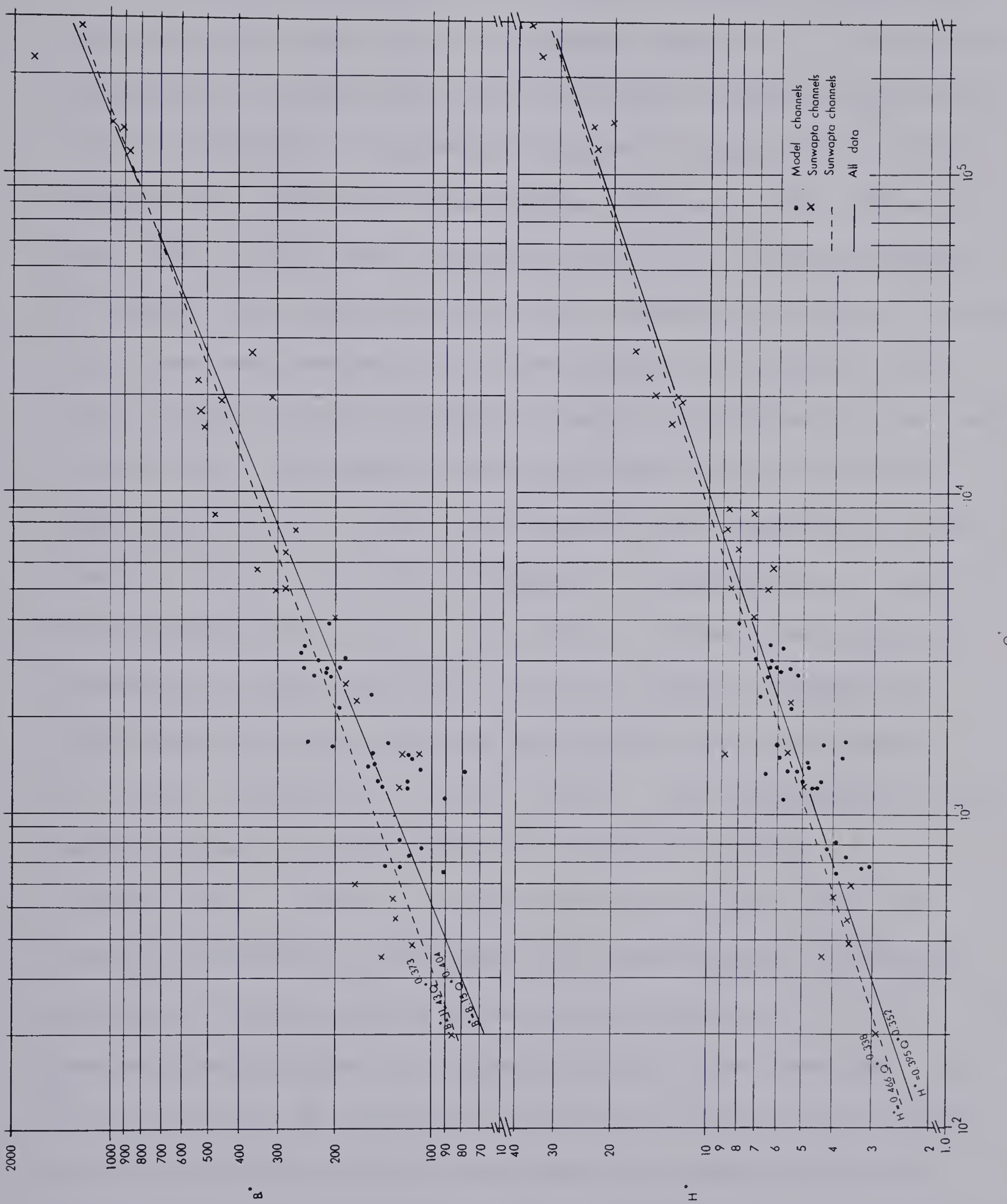
$$B^* = 1.99\ Q^{*0.578} \qquad r^2 = 0.753 \qquad \text{sig.} = 0.01 \qquad (24)$$

$$H^* = 1.11\ Q^{*0.221} \qquad r^2 = 0.699 \qquad \text{sig.} = 0.01 \qquad (25)$$

While the B* v Q* line approaches more closely that for the flume data the H* v Q* line is further away.

In order to ascertain the similarity or otherwise of the regression lines it is possible to compare the a and b coefficients along with their confidence limits. The calculation of confidence limits using the standard error is given in Appendix 3, along with the actual values obtained. In summary it can be said that for both B* and H* there is overlap of the confidence limits of the b coefficients from all four sets of data (all data combined, flume, Sunwapta, and Sunwapta Q* - 10^3-10^4) while in the case of the a coefficients there is not always overlap but in all cases the confidence limits give possible values which are very close to one another. Clearly the

Figure 6.4 Comparison of 'dimensionless hydraulic geometry' of model channels and Sunwapta River data.

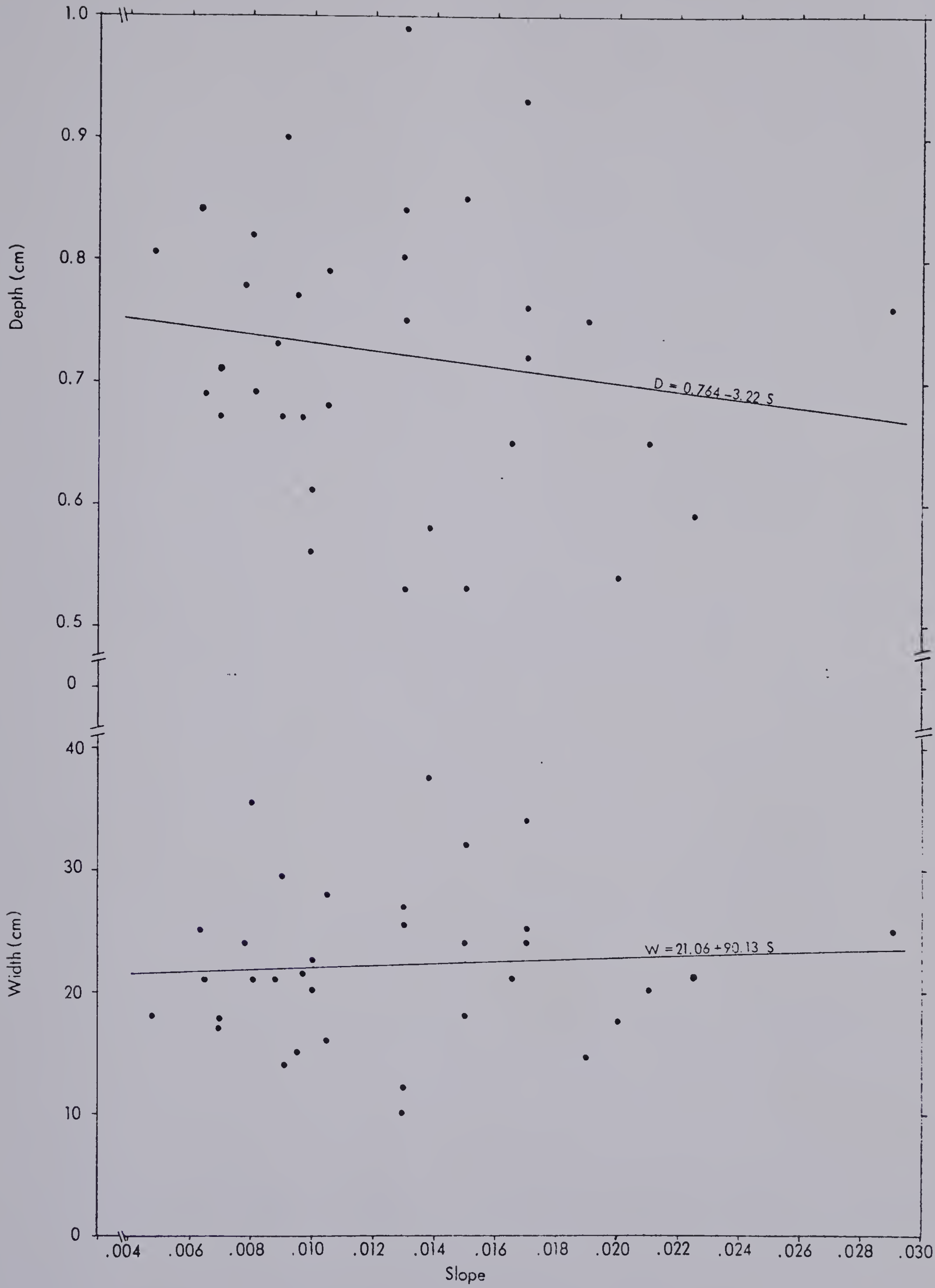


Model channels
Sunwapta channels
Sunwapta channels
All data
B* = 11.42 Q*^0.373
B* = 8.15 Q*^0.404
H* = 0.466 Q*^0.338
H* = 0.395 Q*^0.352
B*
H*
Q*

regression equations from the model and prototype give dimensionless hydraulic geometries very close to one another.

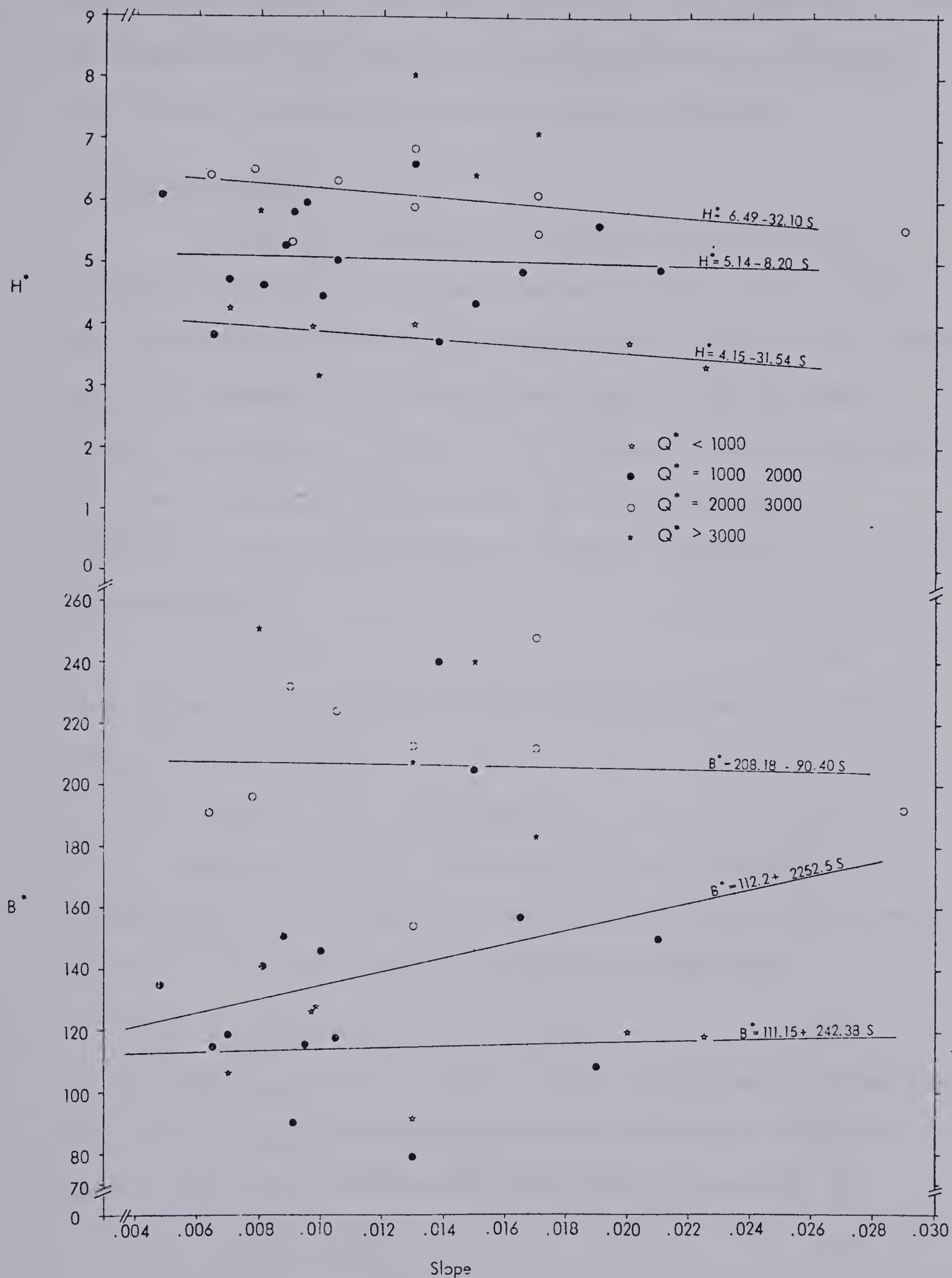
Current explanations of the cause of braiding centre attention on the width/depth ratio of the channel (see p 24). The earlier observations of Leopold and Wolman (1957), that a stream in equilibrium (*i.e.* no aggradation or degradation) braids at slopes above a certain threshold, was confirmed in later studies (Henderson, 1961; Schumm and Khan, 1972) and this ties in with the fact that at constant discharge and sediment size the width/depth ratio increases with slope. The trend should have been observed in the flume channels but, because of variation in grain size and considerable range of discharges, there is large scatter in the relationships between depth and slope and width and slope (see Fig. 6.5). Notice, also, that with the flume set at a given slope the slope of individual anabranches is constrained *i.e.* they are not completely free to adjust their slope. However, the regressions, although by no means significant, do give a negative exponent for depth versus slope and a positive exponent for width versus slope ($W = 21.06 + 90.135\ S$, $D = 0.764 - 3.225\ S$). The relationships can be made more orderly by first using the variables H^* and B^* (defined above, p 116) to allow for variations in grain size, and secondly by splitting up the sample into several groups according to discharge. In this instance Q^* was used but in fact the values of Q would have produced groupings only slightly different from those used. Fig. 6.6 clearly shows the influence of allowing for discharge and regression lines for the individual groups confirm the negative trend of depth with slope and the increase of width with slope at each discharge level (although only the two middle groups $Q^* = 1000$-2000 and $Q^* =$

Figure 6.5 Average width and depth versus water surface slope of model channels.



Depth (cm)
1.0
0.9
0.8
0.7
0.6
0.5
0
D = 0.764 -3.22 S
Width (cm)
40
30
20
10
0
W = 21.06 + 90.13 S
.004
.006
.008
.010
.012
.014
.016
.018
.020
.022
.024
.026
.028
.030
Slope

Figure 6.6 Dimensionless width and depth versus water surface slope. Data stratified using four discharge groups.


H*
9
8
7
6
5
4
3
2
1
0
H* = 6.49 - 32.10 S
H* = 5.14 - 8.20 S
H* = 4.15 - 31.54 S
Q* < 1000
Q* = 1000 2000
Q* = 2000 3000
Q* > 3000
B*
260
240
220
200
180
160
140
120
100
80
70
0
B* = 208.18 - 90.40 S
B* = 112.2 + 2252.5 S
B* = 111.15 + 242.38 S
.004
.006
.008
.010
.012
.014
.016
.018
.020
.022
.024
.026
.028
.030
Slope

2000-3000 have samples large enough for a regression analysis). Again, the regressions are not significant but they do serve to illustrate that despite the scatter the expected trends are evident.

6.5 Flow Resistance

In these flat-bedded gravel channels much of the flow resistance is invested in the particles on the bed. Church (1972) found that where the channel bed remained inactive even at fairly high flows the resistance decreased extremely quickly with increasing relative roughness at a station, but he suggested that the existence of a mobile bed could have a marked effect on this relationship. Resistance to flow in open channels is usually expressed in an equation such as Manning's:

$$V = R^{2/3} S^{1/2} / n \qquad (26)$$

which was derived empirically or in a similar form using the Darcy-Weisbach friction factor:

$$V \propto \sqrt{gRS/ff} \quad \text{or} \quad ff = 8gDS/v^2 \qquad (27)$$

Keulegan's (1938) logarithmic flow law to describe the velocity profile in turbulent open channel flow is also theoretically correct as a resistance equation for two-dimensional flow:

$$\frac{\bar{v}}{V*} = 6 + \left(\frac{1}{K}\right) \log \left({}^{D}/{}_{d}\right) \qquad K = 0.4 \qquad (28)$$

Church (1972) suggested that a more generalized expression of the type $\bar{v} = C_1 R^{C2} S^{1/2}$ may be used to describe the resistance in braided channels and further indicated that this could be expressed as:

$$\frac{\bar{v}}{V*} = C_3 \frac{D}{d}^{C4} = \sqrt{8/ff} \qquad (29)$$

The relationship to the Darcy-Weisbach coefficient is deriv- -ed from $ff = 8gDS/v^2$ and $v = 8gDS/ff$. Using Strickler's relation for

roughness due to particle size in gravel streams ($n = 0.038\, d^{0.167}$) we find that the Manning equation, when all resistance to flow is provided by the particles on the bed, can be expressed as:

$$\sqrt{8/ff} = 8.4 \frac{D}{d}^{0.167} \quad \text{where } d = d_{90} \tag{30}$$

Not only is the size of particles important but their spacing apparently influences resistance also and when closely packed may present an apparently smooth bed to the flow. An active carpet of material may produce the same effect and so influence the resistance relationship. All the model channels showed live beds and for this reason we might expect resistance to change very little with D/d_{90} in comparison with a channel with an inactive bed and, therefore, approach more closely the Manning relation (eq. 30). The regression equation for the flume data (see Fig. 6.7) suggests that this is the case:

$$\sqrt{8/ff} = 8.13 \left(\frac{D}{d_{90}}\right)^{0.25}$$

The resistance for a given D/d_{90} in the model channels is lower than predicted by Strickler's or Keulegan's law and this may be due either to the presence of a mobile boundary or more likely to the restricted range of grain sizes on the model anabranch beds.

6.6 Channel Stability

Parker (1976) proposed that channel division commences when the inequality $D/W \leq S/Fr$ ceases to be satisfied. Calculation of D/W and S/Fr for the stable flume channels shows that all the channels obey this relationship. Those approaching the critical values most closely are (inevitably) those with large width/depth ratios or steep slopes, as would be expected.

However, generally the loss of stability is expressed

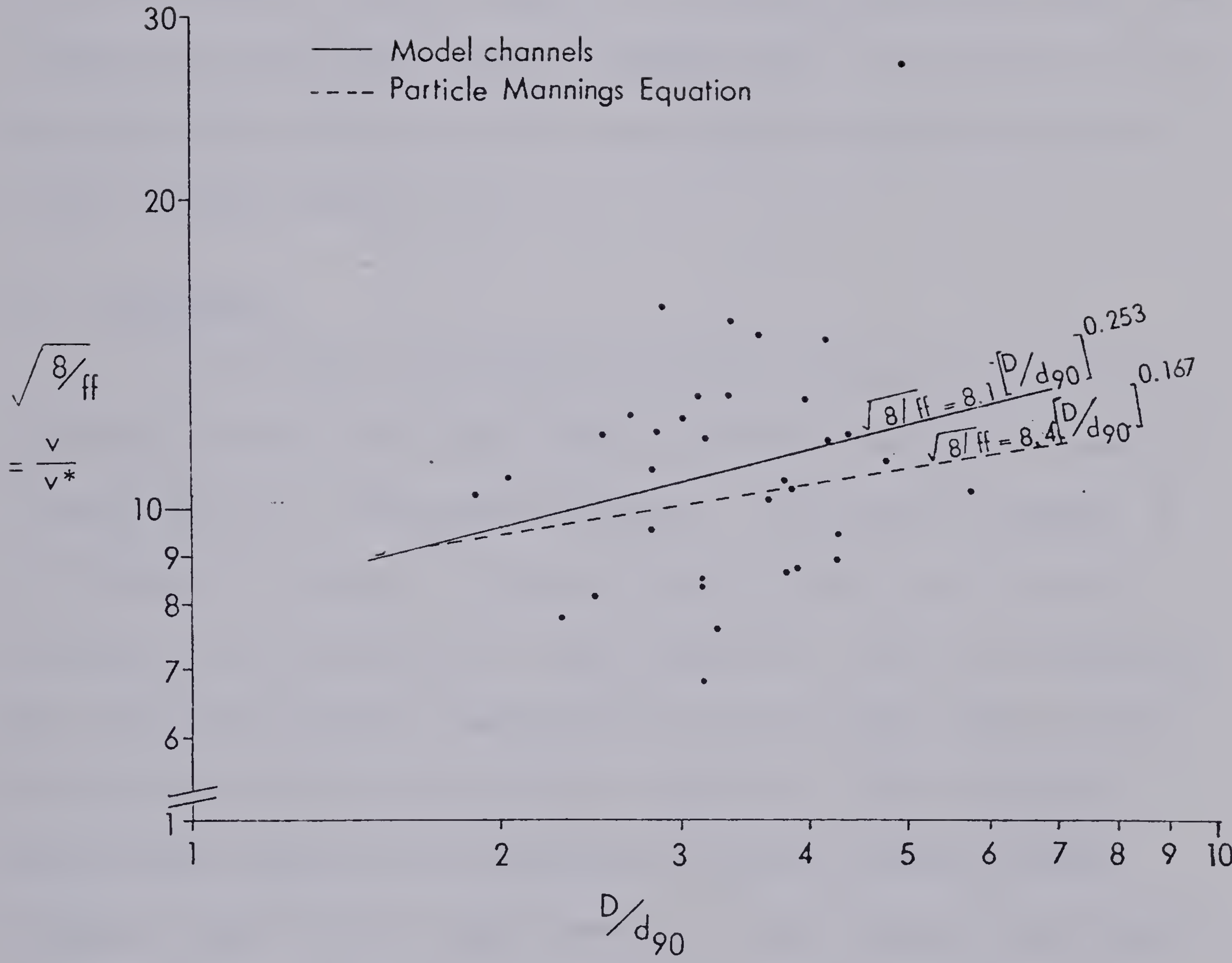


Figure 6.7 Resistance relation for model channels.

not by straightforward division following mid-channel deposition but by the construction of bars and associated channel scour. Channel division then follows from these developments. While the theoretical width/depth ratio applies to the stable channels it does not preclude channel division at values apparently below critical through the reduction of depth and loss of sediment transport capacity following bar development. In this respect it is interesting to note that the channel from which the braiding commenced ($D/W = 0.04$, $S/Fr = c0.013$) was originally within the stable single channel region of Parker's (1976) diagram (his Fig. 4).

6.7 Conclusion

By following approximate scaling relations it is possible to produce a braided river model whose self-formed anabranches resemble closely those of a full-scale prototype. The hydraulic geometry of the channels is similar to that of natural rivers in non-cohesive material and is typified by a rapid increase in width with discharge. By scaling the channels appropriately it can be shown that the model and prototype channels show similar dimensions. Flow resistance changes only slowly with discharge and relative roughness, either because of the live bed which presents a smooth boundary and reduces the influence of grain size on resistance or because of the small range of grain sizes present.

CHAPTER 7. SUMMARY AND CONCLUSIONS

7.1 Introduction

In view of the complexity of braided rivers and the difficulties encountered in field investigations of full-size braided stream processes (Fahnestock, 1963; Hein, 1974; Smith, N.D., 1974) they present an ideal subject for study in a laboratory model in which observations of events are simpler and in which the values of variables such as discharge and slope can be chosen and varied at will. Such models have proved extremely useful in fluvial geomorphology, particularly at a qualitative level. Attempts to compare model and prototype at a more quantitative level are rare, but provided some basic modelling principles (geometric and Froude similarity) are obeyed and Reynolds effects are negligible, there is no reason why self-formed model streams should not be compared directly with full-scale rivers at a quantitative as well as qualitative level. In other words, it should be possible to go beyond Hooke's (1968) process modelling. While comparisons in this study were limited largely to descriptive information, the data on the dimensions of individual anabranches serves to demonstrate the quantitative similarity of model and prototype. Clearly however there is a long way to go before similarity of, say, sediment transport is established although there is probably at least order of magnitude similarity even in the fairly crude model discussed here. The results from this model can be summarized under three headings - pattern development, sediment sorting, and channel form.

7.2 Pattern Development

When started from a straight trench braiding was initiated from a series of regularly spaced, lobate, alternating bars similar to those described from several flume and field studies of both meandering and braided rivers. The common origin of braiding and meandering is implicit in recent theoretical studies of channel pattern (*e.g.* Parker, 1976). At the same time recent literature has pointed to a similarity of sedimentary features in braiding and low-sinuosity meandering rivers in comparable material and this tends to confirm the idea that braiding can be considered as a modification of meandering at high width/depth ratios and/or low relative roughness (D/d_{90}).

The full braided pattern develops when the bends in the sinuous thalweg increase in amplitude and the bars develop to a point where they begin to obstruct the flow. The highest (usually central) portions of the downstream extremity of the bars become too shallow to transport bed load and from nuclei around which flow divides producing two or more active channels in any one cross-section. This is contrary to Leopold and Wolman's (1957) description of the initiation of braiding but channel division of this type was also observed at times during the experiments. Once established the pattern is maintained by the tendency for the channels to continue to develop these lobate/tabular bars which produce channel migration and flow diversion and division. These dynamic lobate bars are the primary expression of sediment deposition and, along with scour pools, should be regarded as the primary element of the braided pattern. They often act as major sediment transport surfaces and their downstream or lateral migration results

from deposition at their margins which show avalanche faces with a height of half the channel depth or more (*i.e.* up to about 1 cm in this model). These bars respond to and in turn produce changes in the flo pattern and in their primary form can be divided up into those which are asymmetrical (the most common) and those which are symmetrical in form with respect to the main current direction. In previous terminology these would be referred to as linguoid or transverse bars (Miall, 1977) and are equivalent to the diagonal and transverse unit bars of Smith, N.D., (1974). Once they become partially or wholly inactive, abandoned or dissected, they may leave simple longitudinal remnants and diagonal riffles or become part of some more complex depositional structure. It is important to distinguish between these active bars and the variety of remnants which remain after they become inactive. Thus, it is advisable to use different terms for the active lobes and the inactive remnants regardless of how much of their original form is preserved so as to avoid the confusion evident in the use of, for example, the term 'longitudinal bar'.

The accumulation of sediment as bars is necessarily associated with upstream scour and in many cases the development of pronounced pools. These may be of two principal types:

1) Channel junction scour - develops where two or more channels converge producing secondary flow cells with downward motion in the centre and upward and outward motion downstream. Bars and small submerged levees develop downstream as a result of scour of sediment and in response to the flow pattern established.
2) Asymmetric scour - associated with asymmetric bars and also found in channel bends. A strong, single, helical, flow cell produces

scour and results in bar deposition immediately downstream.

These basic forms, with a variety of differences in detail, constitute the building blocks for more complex depositional units. Several processes are operative in the development of these lateral and medial complexes and it is possible to recognize depositional forms and relate them to these processes and thus, in some cases at least, build up a picture of events from particular forms as well as observe the actual processes at work. The same basic processes of channel migration, division and avulsion, along with the scour and bar construction, deposition on the inside of bends, and the like may be identified in all complexes. Some point bar and medial bar complexes are recognizable as being built during one continuous series of events while most result from several events and hence show both erosional and depositional features.

The whole system can be viewed as a heirarchy of forms with the scour and deposition sequence occurring on at least two or three different scales. Sequences of aggradation and degradation at a scale comparable with the bend wavelength may be responsible for the fluctuations in sediment yield observed in the flume and may relate to the stepped longitudinal profiles of the sandurs studied by Church (1972).

Observations of approximate rates of bar migration show at least an order of magnitude agreement with comparable rates from natural rivers.

The observations of the manner in which the braided pattern developed, and the similarities to the initiation of meanders in similar material, as well as the sedimentological features which low sinuosity meanders and braids have in common, again brings into focus

the continuum of channel pattern. Not only is there a continuum in plan form (Leopold and Wolman, 1957) but also a parallel continuum in terms of channel processes and sedimentology. Not only do braids and meanders in similar material (in this case, gravel) resemble one another but, also, recent work by Cant and Walker (1978) in the sandy South Saskatchewan River provides descriptions of bar formation which agree very closely with those from the flume channels. In terms of external bar form, at least, sand and gravel braids apparently have something in common, suggesting that bars in both sand and gravel originate in the same way (namely as tabular lobes of sediment).

7.3 Sediment Sorting

During construction of the braided river deposits a certain amount of sorting of sediment by size is inevitable and although superficially rather chaotic there is some recognisable order to the distribution. The fact that some of the patterns observed in the flume have also been described from natural rivers is encouraging in terms of the success of the modelling, all the more so when it is remembered that the sand used in the flume had a fairly restricted size range. Of primary importance is the downstream-fining observed on many active bar surfaces. Its origin remains unclear in the absence of satisfactory measurements but the most likely explanation would seem to be that which relates the sorting to the development of upwards-fining on the avalanche faces of these bars. Recently the 'diffuse gravel sheet' model of the origin of bars and bar stratification in gravel braided rivers has been proposed to explain their initiation and development (Hein and Walker, 1978). This model requires that the finer particles are winnowed from an original by poorly sorted sheet of gravel two or

three grains thick (such features were observed in the flume) thus producing fining downstream across the bar surface. As yet a thorough investigation of the 'diffuse gravel sheet' model has not been attempted. The small number of samples taken from the flume, while agreeing with the surface sorting pattern of the 'diffuse gravel sheet' model, also show very coarse material at the base of the avalanche faces of the bars suggesting that the flow is capable of transporting these large particles across the bar surfaces. If this is the case perhaps we should look for another possible sorting mechanism of which the most likely is associated with the vertical sorting evident on the avalanche faces. If this is the actual mechanism then we might expect only those bars with well-developed avalanche faces to show a clear downstream fining. A resolution of this problem, in favour or against the 'diffuse gravel sheet' model, would be a useful contribution to the understanding of gravel stratification.

The larger scour pools, when active, show no sign of a coarse lag but do have a small amount of extremely fine material which is absent from most other samples. These fines may have been gradually washed down to depths which only the scour holes reach. Once flow in the scour pool begins to decline in strength, coarse material accumulates at the bottom and the pool is gradually infilled with finer particles.

Lateral sorting is also very apparent. Where secondary currents are strong enough to carry bed material it is common to find only the finest sediment taken by these currents and deposits of fines can be found at the margin of bars and channels (where flow is expanding) and downstream of scour holes in the levees constructed by the

secondary flow cells. Under certain circumstances the greater inertia and ease of movement of larger particles is also responsible for sort-int. Thus , for example, at channel divisions and where flow begins to overtop the banks in bends it is the coarser material with the greater inertia which fails to turn with the flow and is carried up on to the inactive surface. Thus, when avulsion commences the first sediment to be carried into the new channel is the coarser material which moves more easily in shallow flow over finer particles.

In explaining the sorting patterns it is important to consider the forces acting on grains once they are in motion, as well as the forces contributing to the initiation of motion, and the fact that larger particles may be more easily moved than finer ones.

Since they are the main component of braided river deposits it is perhaps most important that the distribution of grain sizes in active bars be fully understood.

7.4 Channel Form

Channel dimensions and discharge measured in 34 channels at approximately equilibrium revealed a hydraulic geometry similar to that of other streams in non-cohesive material but with a rather higher width exponent than is commonly the case. The hydraulic geometry is equivalent to a downstream type and the values obtained were close to those of theoretical and empirical downstream hydraulic geometries in non-cohesive material. When scaled appropriately, using d_{50} as the principle scaling factor, the data agree closely with similarly scaled 'prototype' data from the Sunwapta River, Alberta. This again is encouraging in terms of the reality of the model.

Reynolds numbers for all channels were high enough to be

assured of fully turbulent flow and viscous scale effects were consequently minimal. Froude numbers, although all supercritical, are not abnormal for shallow, steep channels.

All the channels show D/W v S/Fr values below critical for braiding and thus tend to confirm Parker's (1976) criterion. Pattern instability originates mainly as a result of bar formation and while the width/depth ratio remains at the centre of the braiding threshold it is common for the decrease in depth, as a result of bar deposition, to produce channel division. In other words there are two forms of instability - the first involves an increase in width/depth ratio to allow the development of regular velocity perturbations and alternating bar development and, the second is an increase in width/depth ratio at constant discharge which produces deposition in the centre of the channel. Both lead to channel division and hence braiding. Rarely does a channel remain devoid of bar development to allow braiding from this second source, although it is common for this type of mechanism to produce the first channel division in a braided reach. In other words channel divison associated with active bar lobes is far more common than the classical Leopold and Wolman (1957) type.

7.5 Concluding Remarks

The extent to which it has been possible to model gravel braided river processes in a small flume points to this approach as being of considerable value in the future. At the same time the present model is a little crude in some respects and in particular improvements to the sediment feed and discharge systems are desirable. Meanwhile, in terms of the modelling itself a larger range of sediment size, a larger flume width and deeper flow (*i.e.* an increase in the

size of the model) would help improve both the standard of modelling as well as easing some measurement problems.

While model studies may not be as adventurous as field work they can certainly be equally fruitful. Perhaps the greatest advantage of the model in this study lies in the understanding at a qualitative level of the assemblage of processes responsible for the bewildering array of depositional forms present in braided rivers. Comparison of the forms in the model with descriptions and illustrations from natural rivers show the accuracy with which the model reproduces these forms. The model also holds promise in considering problems such as the influence of slope, sediment size and fluctuating discharge on the characteristics of braided rivers. But, it has also been shown that by obeying basic modelling criteria it is possible to produce channel geometry which is very close to that of prototype rivers and channel migration and bar migration rates at least in the same order of magnitude as those of prototype rivers. The quantitative similarity of the more detailed aspects of, for example, sediment transport rates has yet to be verified. Perhaps the greatest value of the model lies in the clarity with which processes can be observed and the provision of a perspective which allows a better picture of events to be assembled than is possible in the field. Thus, the model is a source of ideas to be tested in the field.

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APPENDIX 1. SUMMARY OF SUNWAPTA RIVER DATA

Discharge (cm^3/s)	Width (m)	Depth (m)	d_{50} (mm)	Q*	B*	H*
7.38	13.46	0.35	26.91	$1.60x10^4$	500.18	13.00
2.48	7.16	0.22	39.67	$2.61x10^3$	180.49	5.55
3.97	6.02	0.49	55.71	$1.51x10^3$	108.06	8.79
1.53	6.10	0.20	35.75	$2.22x10^3$	170.63	5.59
3.12	7.42	0.27	37.27	$4.00x10^3$	199.09	7.24
0.42	4.84	0.15	34.29	$3.56x10^2$	141.15	4.37
1.97	7.87	0.25	69.55	$3.86x10^2$	113.16	3.59
0.98	5.84	0.20	68.59	$2.00x10^2$	85.14	2.92
1.89	5.94	0.28	46.85	$1.21x10^3$	126.79	5.98
14.16	18.90	0.45	37.01	$1.84x10^4$	510.67	12.16
1.00	6.60	0.19	51.98	$4.69x10^2$	126.97	3.65
9.23	19.51	0.30	41.64	$8.47x10^3$	648.54	7.20
1.22	7.57	0.18	20.82	$8.71x10^3$	363.59	8.65
0.87	4.17	0.19	33.59	$1.53x10^3$	124.14	5.66
1.34	7.87	0.17	25.99	$4.96x10^3$	302.81	6.54
3.25	8.99	0.26	32.00	$6.50x10^3$	280.94	8.12
0.83	5.08	0.17	19.29	$7.54x10^3$	263.35	8.81
0.45	6.30	0.13	36.76	$6.00x10^2$	171.38	3.54
0.33	4.47	0.14	34.29	$5.41x10^2$	130.36	4.08
2.73	6.56	0.31	20.97	$1.95x10^4$	312.83	14.78
8.51	16.08	0.47	13.00	$2.84x10^5$	1236.90	36.15
0.40	5.03	0.15	17.75	$5.00x10^3$	283.38	8.45
1.62	5.64	0.27	16.00	$2.70x10^4$	352.50	16.87
1.78	9.07	0.26	17.15	$2.22x10^4$	528.86	15.16
0.57	6.63	0.12	19.03	$5.70x10^3$	348.39	6.32
0.58	5.64	0.16	12.73	$1.93x10^4$	443.05	12.57
1.14	7.09	0.19	8.28	$1.14x10^5$	856.30	22.90
1.36	7.70	0.20	8.57	$1.36x10^5$	898.50	23.30
4.48	18.90	0.37	10.93	$2.24x10^5$	1729.18	33.85
5.65	13.57	0.42	13.93	$1.41x10^5$	974.16	30.15

APPENDIX 1. SUMMARY OF MODEL CHANNEL DATA

Discharge (cm^3/s)	Width (cm)	Depth (cm)	Average Velocity (cm/s)	Water Surface Slope	Width/ Depth	B*	H*	Q*	ff	d_{90} (mm)	D/d_{90}	d_{50} (mm)	Froude no.	Reynolds no. Re	Reynolds no. Re*	Depth/ Width	Slope/ Froude no.
479.7	21.0	0.69	33.1	.0065	30.4	115.4	3.80	1480.0	.0321	.241	2.86	1.82	1.27	2283.9	50.56	.033	.0051
343.9	16.0	0.68	31.5	.0105	23.5	118.5	5.04	1270.0	.0565	.239	2.85	1.35	1.22	2142.0	63.25	.043	.0090
938.3	25.5	0.99	37.1	.0130	25.7	207.3	8.05	3890.0	.0734	.172	5.76	1.23	1.19	3672.9	61.12	.039	.011
331.8	15.0	0.77	28.6	.0095	19.5	116.3	5.97	1520.0	.0702	.203	3.79	1.29	1.04	2202.2	54.38	.051	.009
372.6	21.0	0.65	27.4	.0165	32.3	156.7	4.85	1410.0	.1120	.206	3.15	1.34	1.08	1781.0	66.82	.031	.015
360.2	17.8	0.71	28.6	.0070	25.1	105.9	4.23	774.0	.0477	.229	3.10	1.68	1.08	2030.6	50.56	.040	.006
664.6	28.0	0.79	29.8	.0105	35.4	224.0	6.32	2990.0	.0733	.207	3.82	1.25	1.07	2354.2	59.05	.028	.010
306.6	10.0	0.84	36.5	.0130	11.9	78.7	6.61	1330.0	.0643	.177	4.75	1.27	1.27	3066.0	50.81	.084	.010
946.5	35.5	0.82	32.4	.0080	43.3	251.8	5.82	3150.0	.0490	.207	3.96	1.41	1.14	2656.8	52.51	.023	.007
426.3	18.0	0.81	29.0	.0048	22.2	135.3	6.09	1650.0	.0363	.229	3.54	1.33	1.03	1458.0	44.72	.045	.005
706.6	25.0	0.84	33.8	.0064	29.8	190.8	6.41	2830.0	.0369	.203	4.14	1.31	1.18	2839.2	46.62	.034	.005
752.4	24.0	0.93	33.7	.0170	25.8	183.2	7.10	3010.0	.0109	.189	4.42	1.31	1.12	3134.1	74.43	.039	.015
422.1	14.0	0.90	33.5	.0091	15.6	90.3	5.80	1110.0	.0573	.207	4.35	1.55	1.13	3015.0	58.67	.064	.008
376.2	17.0	0.67	32.9	.0070	25.4	118.9	4.68	1210.0	.0340	.201	3.33	1.48	1.28	2204.3	43.11	.039	.005
400.9	21.5	0.67	27.6	.0097	31.8	125.7	3.94	825.0	.0670	.239	2.80	1.71	1.07	1849.2	60.35	.031	.009
363.7	22.5	0.56	28.8	.0099	40.2	127.1	3.16	686.0	.0525	.210	2.67	1.77	1.23	1612.8	48.97	.025	.008
170.1	12.0	0.53	26.6	.0130	22.6	90.2	3.98	656.0	.0765	.287	1.88	1.33	1.17	1409.8	74.61	.044	.011
240.3	17.5	0.54	25.6	.0200	32.4	119.9	3.70	733.0	.1290	.234	2.31	1.46	1.11	1382.4	76.17	.031	.018
373.6	20.0	0.65	28.1	.0210	30.8	150.4	4.89	1440.0	.1360	.201	3.24	1.33	1.11	1826.5	73.55	.033	.019
547.0	25.0	0.72	30.2	.0170	34.7	211.8	6.10	2850.0	.1053	.189	3.81	1.18	1.14	2174.4	65.49	.029	.015
637.9	27.0	0.75	31.6	.0130	36.0	212.6	5.90	2760.0	.0766	.206	3.64	1.27	1.16	2370.0	63.72	.028	.011
365.3	21.0	0.59	29.7	.0225	35.6	118.0	3.31	678.0	.1180	.239	2.47	1.78	1.23	1752.3	86.25	.028	.018
621.0	29.5	0.67	31.4	.0090	44.0	232.3	5.28	2690.0	.0480	.201	3.33	1.27	1.22	2103.8	48.89	.023	.007
358.1	14.5	0.75	32.8	.0190	19.3	108.2	5.59	1360.0	.1040	.192	3.91	1.34	1.21	2460.0	71.79	.052	.016
651.8	37.5	0.58	29.9	.0138	64.6	240.4	3.72	1680.0	.0703	.285	2.09	1.56	1.25	1734.2	79.86	.015	.011
436.8	18.0	0.80	30.3	.0130	22.5	153.8	6.84	2320.0	.0889	.187	4.28	1.17	1.08	2424.0	59.73	.044	.012
352.5	20.0	0.61	28.9	.0100	32.8	146.0	4.45	1260.0	.0570	.244	2.50	1.37	1.18	1762.9	59.69	.031	.008
600.0	25.0	0.76	31.6	.0290	32.9	192.3	5.55	2140.0	.1730	.242	3.14	1.37	1.16	2401.6	112.53	.030	.025
790.4	34.0	0.76	30.5	.0170	44.7	248.2	5.55	2820.0	.1090	.242	3.14	1.37	1.12	2318.0	86.15	.022	.015
861.1	32.0	0.85	31.7	.0150	37.6	240.6	6.39	3320.0	.0996	.200	4.25	1.33	1.10	2694.5	70.73	.027	.014
341.3	24.0	0.53	26.7	.0150	47.2	204.9	4.34	1630.0	.0875	.189	2.80	1.22	1.17	1415.1	52.78	.022	.013
534.3	24.0	0.78	28.4	.0078	30.8	196.7	6.50	2660.0	.0592	.187	4.17	1.20	1.03	2215.2	45.68	.033	.008
450.7	21.0	0.73	29.5	.0088	28.8	151.1	5.25	1550.0	.0597	.231	3.16	1.39	1.10	2153.5	57.99	.035	.008
418.5	21.0	0.69	28.9	.0081	30.4	140.9	4.63	1210.0	.0525	.230	3.00	1.49	1.11	1994.1	53.85	.033	.007

APPENDIX 2. SEDIMENT SIZE DATA SUMMARY

	% of sample in ø classes															
Sample	<1.75	1.75- 1.5	1.5- 1.25	1.25- 1.0	1.0- 0.75	0.75- 0.5	0.5- 0.25	0.25- 0	0- -0.25	-0.25- 0.5	0.5- -0.75	-0.75- -1.0	-1.0 -1.25	-1.25- -1.5	-1.5- -1.75	-1.75- -2.0
Channel 1							0.5	3.1	10.8	15.7	12.5	16.4	27.7	13.4		
2						1.0	2.2	9.5	22.1	20.6	16.2	3.9	13.2	11.1		
3					1.0	2.0	4.4	12.4	24.0	26.4	13.1	17.7				
4					0.21	0	1.7	11.6	25.6	25.0	18.7	4.0	13.3			
5							0.9	13.5	25.2	16.1	21.2	6.5	16.5			
6						0.1	0.7	5.1	12.0	16.5	15.4	20.8	22.0	7.4		
7					0.1	0.3	3.5	14.3	26.8	18.6	13.4	3.8	19.1			
8					0.3	1.0	3.4	9.6	22.2	31.8	21.0	3.9	6.7			
9					0.1	0.3	0.2	6.1	23.9	20.6	17.3	11.7	19.9			
10						0.3	0.2	6.6	23.9	27.9	13.1	19.0	0	9.9		
11					0.2	1.0	1.7	8.5	24.4	23.2	16.1	11.7	13.1			
12					0.1	0.8	1.5	11.9	23.3	23.3	12.4	20.9	5.9			
13							0.8	5.1	23.3	17.1	10.3	14.0	29.4			
14						0.7	2.5	5.8	20.4	18.8	22.3	18,9	10.6			
15					0.1	0.4	0.2	5.8	13.0	15.7	13.2	12.4	25.2	14.1		
16							0.4	1.4	9.2	12.1	17.0	30.7	29.1			
17						0.3	0.9	9.3	17.2	34.3	9.0	9.2	5.2	0	14.7	
18						0.3	1.6	9.3	19.2	15.6	20.6	3.2	21.4	9.0		
19						2.0	2.5	11.6	16.7	28.0	11.2	15.2	12.8			
20						0.7	0.3	12.8	37.1	14.2	11.9	16.2	6.8			
21					0.1	1.5	4.2	8.1	26.9	21.9	12.3	4.2	21.0			
22					0.1	0.3	0.1	1.8	11.3	13.3	17.1	18.1	27.5	10.3		
23				0.1	0	0.2	0.5	10.0	29.0	25.0	12.6	10.7	12.0			
24						0.3	2.0	9.0	23.0	22.8	16.1	20.5	5.8			
25							0.8	4.4	11.8	20.6	22.7	13.6	15.3	0	10.8	
26						0.3	2.0	11.0	40.1	16.5	11.8	11.8	6.6			
27						0.1	2.1	5.4	22.8	22.8	14.0	5.9	10.0	16.8		
28						1.4	1.6	5.6	16.4	27.6	13.2	14.0	4.7	15.5		
29							0.3	2.1	8.0	21.7	20.9	8.8	11.9	10.0	16.4	
30							0.5	1.3	8.4	23.8	23.1	8.8	24.0	10.1		
31						1.2	1.7	15.5	27.3	25.7	6.8	15.4	6.5			
32					0.2	1.3	2.1	16.3	27.0	27.8	9.9	8.3	7.0			
33						0.7	1.4	9.7	20.8	18.7	13.7	19.9	5.6	9.4		
34				0.4	0	0.1	0.9	4.4	22.5	16.3	18.2	12.9	17.4	7.3		
Bar																
Upstream 1		0.4	0	0.1	0.1	1.5	2.6	5.7	24.6	18.8	15.8	10.0	11.3	9.5		
2						0.1	0.3	3.1	12.0	22.5	20.3	27.5	7.7	6.5		
3						0.6	0.9	5.3	20.9	20.9	18.5	18.8	5.3	8.9		
4				0.1	0	1.5	3.4	9.5	25.5	16.9	19.7	11.1	12.5			
5						0.3	1.9	5.6	21.2	22.2	18.7	17.2	4.8	8.2		
6						1.0	2.7	10.4	27.1	18.3	13.2	14.9	12.5			
7						0.2	1.2	6.8	20.9	17.6	16.4	5.6	23.5	7.9		
Bar																
Downstream 1						0.4	3.4	11.7	38.4	26.7	4.7	8.0	6.7			
2				0.1	0	0.8	3.3	16.5	28.2	29.5	13.8	0	7.9			
3						0.1	0.2	1.8	15.8	18.0	25.9	21.9	16.4			
4						1.2	2.0	16.8	40.4	19.4	10.9	9.2				
5							0.6	13.2	40.4	21.7	13.7	3.9	6.5			
6							1.0	9.8	20.5	39.4	18.7	10.5				
7						1.0	5.9	17.4	42.5	21.2	6.5	5.5				
Bar 8																
Upstream Surface						0.1	0.3	2.1	7.8	20.0	15.5	21.9	25.9	6.2		
Center Surface						0.2	0.5	9.9	24.8	32.1	6.0	16.9	0	9.6		
Downstream Surface							0.2	5.9	30.3	28.3	19.1	16.1				
Upstream Base					0.1	0.7	0.8	12.2	26.4	23.5	17.6	0	18.8			
Centre Base				0.2	0.6	1.1	1.6	5.8	15.3	30.2	5.6	12.7	26.9			
Downstream Base							0.4	1.3	8.2	17.5	29.5	39.5	3.5			
Bar edge				0.1	0.7	6.8	11.1	24.0	42.3	15.0						
Pool/Channel Sorting																
Pool 1		0.2	0.1	0.1	0.1	0.3	0.7	8.3	22.8	25.2	18.2	6.8	17.3			
2	.014	0.1	0.04	0.1	0.3	0.8	2.1	9.8	31.8	20.8	10.0	16.9	7.1			
3		0.1	0.5	1.0	1.9	1.4	1.1	7.5	21.5	12.7	9.1	25.3	17.4			
4		0.04	0.3	0.9	4.8	7.3	2.1	8.2	34.3	5.7	8.8	14.9	12.6			
High flow 5	0.4	0.5	0.3	0.2	2.8	4.3	3.5	13.7	28.2	14.1	23.7	8.0				
Low flow 5		0.01	0	0	0	0	0	1.1	8.5	16.7	30.8	24.9	11.5	6.4		
Channels 1		0.02	0.03	0.1	0.5	1.2	1.7	9.2	21.4	18.0	20.2	10.3	17.3			
2				0.2	1.0	1.2	2.5	7.5	21.6	28.2	9.0	11.5	6.5	10.9		
3		.014	0.02	0	0.1	0.7	0.6	4.2	18.1	20.3	10.8	10.5	22.1	0	12.6	
4						0.9	2.7	11.5	38.6	20.2	9.7	16.4				
5				0.1	0.4	1.6	3.3	15.6	42.8	19.8	6.1	10.3				
Abandoned Sheet																
Upstream							1.0	13.8	25.9	21.8	13.0	18.3	6.2			
Downstream							0.1	0	6.8	14.8	14.7	31.1	23.6	8.8		
Coarse Bar/ Fine Channel																
Bar						0.1	0.4	2.0	8.6	13.8	21.1	25.0	24.1	5.1		
Channel				0.1	0	4.1	6.3	21.4	28.1	30.8	3.5	5.8				
Channel/ Levee																
Levee						0.8	5.7	28.2	44.5	17.1	3.6					
Channel						0.5	2.4	6.0	22.0	34.4	13.3	15.1	6.4			
Channel Div.																
L.							0.6	7.5	19.2	20.6	23.1	19.6	9.4			
R.						0.1	0.2	5.7	23.1	33.8	6.9	20.4	9.8			
Centre							0.1	0.5	3.2	9.9	16.6	30.7	28.1	10.9		
Waning Flow Scour																
Pool							0.2	3.3	18.6	12.8	16.2	29.7	19.3			
Levee						2.1	9.8	16.0	46.1	18.9	7.1					
Vertical Sorting																
Top						1.2	3.1	21.0	49.5	18.9	6.4					
Middle						0.2	2.4	17.3	41.5	29.9	8.4					
Bottom			0.024	0.04	0.1	0.1	0.6	5.9	21.4	18.9	11.2	24.3	4.6	0	12.9	
Avalanche Foreset																
Top						0.7	1.8	14.4	34.0	18.6	16.8	0	13.7			
Bottom							0.2	0.6	4.8	11.0	27.2	31.2	25.0			

Appendix 3. Calculation of Confidence Limits of a and b Coefficients (see Doornkamp and King, 1971)

a and b coefficients are established with varying degrees of confidence according to the level of correlation and the size of the sample.

$$\text{Variance of} \quad b = \frac{\sigma_\varepsilon^2}{\Sigma(x_i-\bar{x})^2}$$

σ_ε^2 = variance of the residuals

x_i = any value of x

$\bar{x}$ = mean of x

Standard error of b = $\sqrt{\text{variance}}$

$$\text{Standard error} \quad b = \frac{\sigma_\varepsilon}{\Sigma(x_i-\bar{x})^{2\ \frac{1}{2}}}$$

Usually only an estimate (S^2) of σ_ε is used giving the estimated

$$\text{standard error of} \quad b = \frac{S}{\Sigma(x_i-\bar{x})^{2\ \frac{1}{2}}}$$

Assuming residual values (E_i) are normally distributed then it can be shown that 100 $(1-\alpha)$% confidence limits can be established for b by multiplying standard error of b by the t-value for $(n-2, 1-\frac{1}{2}\alpha)$ where this is $(1-\frac{1}{2}\alpha)$% points of a t distribution with (n-2) degrees of freedom.

The level $\frac{1}{2}\alpha$ is taken since the test is one tailed *i.e.* used to establish only a difference between b and o, not the direction of the difference.

Same applies to a

$$\text{Standard error} \quad a = \left(\frac{\Sigma x_i^2}{n\Sigma(x_i-\bar{x})^2}\right)^{\frac{1}{2}} \sigma_\varepsilon$$

$a \pm t(n-2, 1-\frac{1}{2}\alpha)$ standard error a

let $\alpha = 0.05$ therefore $1-\frac{1}{2}\alpha = 0.975$

Example: If $b = 0.5$, the standard error of $b = 0.085$ and the t-value for n-2 degrees of freedom at the 95% confidence limit is 2.3, then:

$$b = 0.5 \pm 0.196 \text{ at the 95\% confidence limit}$$

standard error of $a = 0.03$,

If $a = 3.5$, $\alpha = 0.05$ and $(1-\frac{1}{2}\alpha) = 0.975$, then the t-value for n-2 degrees of freedom is again 2.3, then:

$$a = 3.5 \pm 0.069$$

APPENDIX 3. 95% CONFIDENCE LIMITS OF a AND b COEFFICIENTS IN DIMENSIONLESS HYDRAULIC GEOMETRY

(equations 18–25)

		All data	Flume data	Sunwapta data	Sunwapta $Q^* = 10^3 - 10^4$
B*	a	8.03<8.16<8.28	3.22<3.66<4.10	11.25<11.43<11.61	1.20<1.99<2.78
	b	0.368<0.404<0.440	0.37<0.505<0.642	0.33<0.37<0.42	0.36<0.58<0.80
H*	a	0.305<0.395<0.485	0.06<0.37<0.68	0.35<0.47<0.58	0.74<1.11<1.48
	b	0.327<0.352<0.377	0.24<0.34<0.44	0.31<0.34<0.37	0.12<0.22<0.325